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2-PHASE EXTRACTION AND GAS-PHASE BIOREACTOR TREATMENT OF TCE IN SOIL AND GROUNDWATER

F.E. WARREN AFB, WYOMING

VOLUME I
TEXT

Prepared for:

Air Force Center for Environmental Excellence
Technology Transfer Division
Brooks Air Force Base, Texas

Prepared by:

Radian International
Austin, Texas

February 1996

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Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
FEB 1996	**Technical**	**00-00-1995 to 00-00-1996**

4. TITLE AND SUBTITLE	
2-Phase Extraction and Gas-Phase Bioreactor Treatment of TCE in Soil and Groundwater F.E. Warren AFB, Wyoming	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Radian International,8501 Mopac Boulevard,Austin,TX,78720-1088**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Air Force Center for Environmental Excellence Technology Transfer Division**	10. SPONSOR/MONITOR'S ACRONYM(S) **AFCEE/ERT**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report (volume 1 of 2) documents a test of the high vacuum 2-PHASE? Extraction (2-Phase) process for the removal of trichloroethene (TCE) in soil and groundwater that was conducted at F.E. Warren Air Force Base (AFB), Wyoming. TCE offgased from the 2-Phase system was treated using a vapor phase bioreactor. Dual phase and pump and treat extraction were also tested for comparison to the 2-Phase system to determine which system would be most suitable for use at F.E. Warren AFB. The integration of the 2-Phase system with the vapor-phase bioreactor was successful. Greater than 95% of dissolved TCE in groundwater was stripped into the vapor-phase by the 2-Phase process. Activated carbon was used to remove the small residual. Groundwater concentrations ranged from 100-1000 ?g/L during the test. The gas-phase reactor demonstrated 85% to 90% TCE removal efficiencies at inlet TCE concentrations ranging from 10-700 ?g/L (@17.7 psia and 150 deg F). Because the comparison objective was added to the scope after the Treatability Study Test Design was complete, it was not possible to make definitive comparisons between the three system types due to the evolution of the scope of the project. However, based on this test, process knowledge and experiences at other sites the following conclusions were drawn: 2-Phase is likely to be more cost effective in tighter formations, and pump and treat or traditional (low vacuum) dual phase is likely to be more cost effective in more productive formations.

15. SUBJECT TERMS
2-PHASE extraction, TCE, trichloroethene, trichloroethylene, DNAPL, bioreactor, pump and treat,treatability study,F. E. Warren AFB, dual phase extraction, groundwater remediation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**65**	

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LIST OF ACRONYMS

2-Phase	2-PHASE™ Extraction
AFB	Air Force Base
AFCEE/ERT	Air Force Center for Environmental Excellence Technology Transfer Division
BPU	Board of Public Utilities
BSMA	Basal salts medium A
BSMB	Basal salts medium B
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfm	cubic feet per minute
ECD	Electron capture detector
FID	Flame ionization detector
GAC	Granulated activated carbon
GC	Gas chromatograph
GC/PID	Gas chromatograph/photoionization detector
gpm	gallons per minute
GPR	Gas phase reactor
Hg	Mercury
IRA	Interim Remedial Action
K	Hydraulic conductivity
N	Nitrogen
OU	Operable Unit
P	Phosphorus
PVC	Polyvinyl chloride
S	Storage coefficient
scfm	standard cubic feet per minute
SVE	Soil vapor extraction
TCE	Trichloroethene
TKN	Total Kjeldahl nitrogen
TOC	Total organic carbon
TSS	Total suspended solids
TSTD	2-Phase Vacuum Extraction and Vapor Phase Biotreatment Treatability Study Test Design

LIST OF ACRONYMS (Continued)

U.S.G.S.	United States Geological Survey
VOA	Volatile organic analysis
VOC	Volatile organic compound

Section 1
INTRODUCTION

1.1 Purpose

The Air Force Center for Environmental Excellence at Brooks Air Force Base (AFB), Texas, Technology Transfer Division (AFCEE/ERT), is testing and evaluating innovative technologies for remedial action that have potentially widespread applicability. Radian International was selected to demonstrate the high vacuum 2-PHASE™ Extraction[1] process (2-Phase) for the removal of trichloroethene (TCE) in soil and groundwater, integrated with vapor-phase bioreactor treatment of TCE in the offgas. The test was designed to also include a comparison of 2-Phase, dual phase, and pump and treat extraction technologies. The test was conducted over a 2.5-month period at F.E. Warren AFB in Cheyenne, Wyoming. The site location is shown in Figure 1-1.

AFCEE and F.E. Warren AFB wanted to identify feasible treatment alternatives for various TCE-contaminated areas on Base and at other locations. Specifically, they were interested in demonstrating the effectiveness of high vacuum 2-Phase extraction at removing TCE and other volatile organic compounds (VOCs) from the subsurface of the Operable Unit 2 (OU 2), Plume C site and treating the TCE in the vapor phase with a bioreactor. AFCEE also wanted to compare the 2-Phase extraction technology with both dual phase (pump and treat combined with vacuum on the well bore) and conventional pump and treat.

1.2 Summary

Radian International (Radian) and our subcontractor, Envirogen, Inc. (Envirogen), demonstrated that the 2-Phase extraction process can be used to remediate TCE and other VOCs in this moderate permeability formation, and that TCE vapors produced by the system could successfully be biotreated by Envirogen's gas-phase reactor. Although the contaminant (TCE) concentration in the extracted vapors was lower than expected, the concentration was within the bioreactor's operational range, and concentrations were artifically increased to within a range that was significant enough to evaluate bioreactor performance properly. Results of the tests also were used to determine radii of influence, contaminant removal rates, and enhanced groundwater extraction rates for application at similar sites. Results of the groundwater pump and treat test were used to determine well yield and aquifer characteristics.

All extraction wells, piezometers, and vapor probes were installed in September 1995; equipment was setup during the last week in September. Envirogen inoculated the bioreactor in early October. Radian conducted the groundwater pump and treat test 1-5 October, the dual phase test 7-18 October, and the 2-Phase test 18 October-15 December. Envirogen received the generated vapors during the dual phase and 2-Phase tests for treatment in the bioreactor, and spiked the bioreactor system with higher concentrations of TCE during the last week of the 2-Phase test in December.

1.3 Site Background

This section describes the general hydrogeology of F.E. Warren AFB and the site-specific geology as shown in the boring logs for the piezometers on site.

[1] 2-PHASE Extraction is a registered trademark of Xerox.

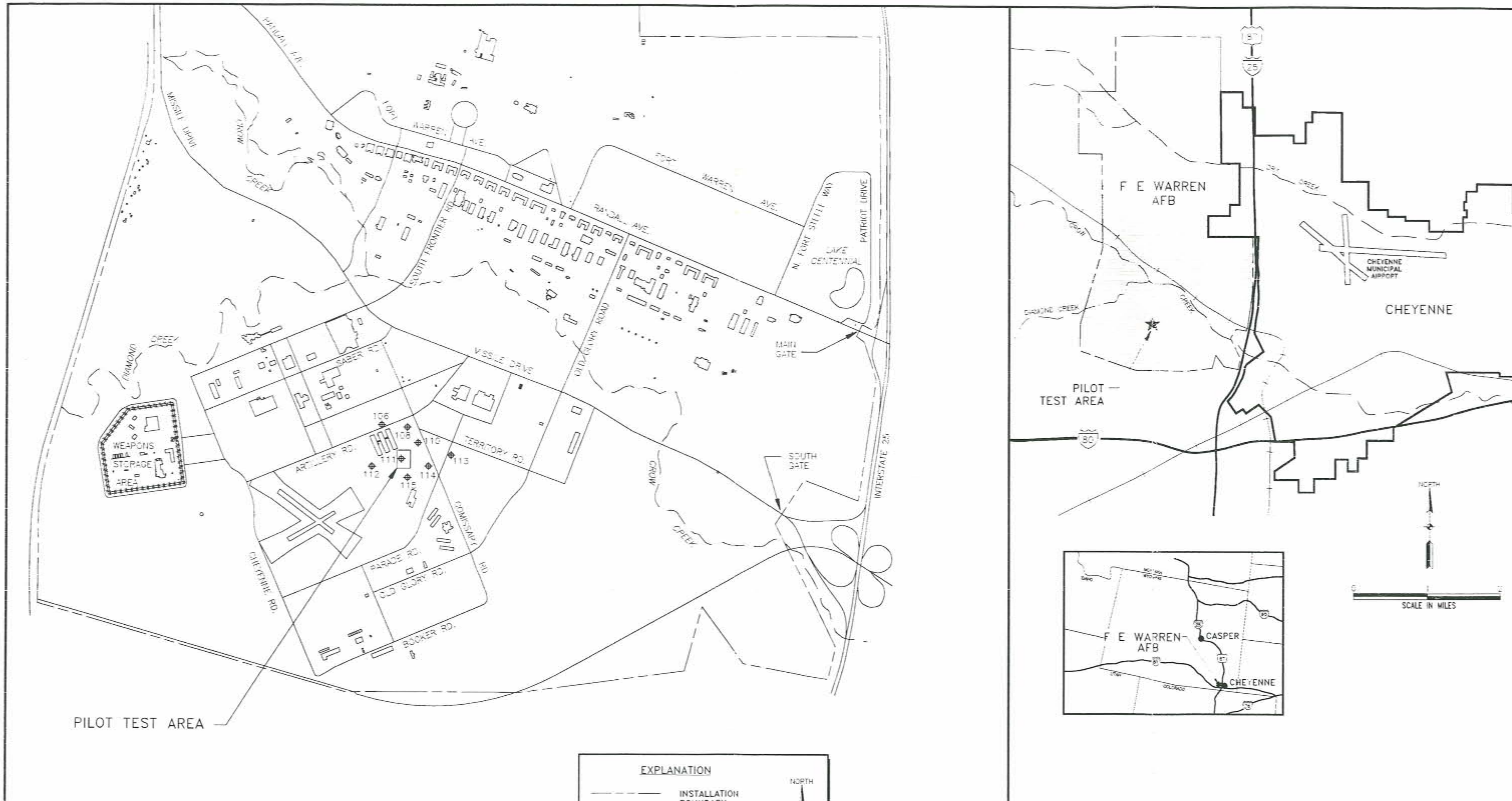

Figure 1-1. SITE LOCATION

F. E. WARREN AIR FORCE BASE
WYOMING

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1.3.1 General Geology

The geology of F.E. Warren AFB consists of Quaternary-age terrace and alluvial deposits composed of clay, silt, sand, and gravel, with some boulders. The thickness of these Quaternary deposits is generally 25 ft or less across the installation. The unconsolidated Quaternary deposits are underlain by the Tertiary-age Ogallala Formation, which has an estimated thickness of approximately 300 ft beneath the Base. The upper part of the Ogallala formation consists of silty clay, with slightly consolidated sand and gravel layers interbedded with clay and silt. The lower part of the Ogallala formation primarily consists of sandstone and conglomerate. The regional dip of the Ogallala formation is to the northeast at about 52 ft per mile (U.S.G.S., 1991).

Groundwater is present in both the unconsolidated Quaternary sediments and the underlying Ogallala formation. Wherever the Quaternary deposits are saturated, they are hydraulically connected to the Ogallala formation. Together, the Quaternary deposits and the Ogallala formation comprise the High Plains aquifer. Water levels are generally less than 20 ft below the ground surface (bgs), but can range up to about 40 ft deep. Much of the recharge in the area comes from direct infiltration of precipitation. Historically, heavy rainfalls have caused water levels to rise rapidly in wells screened in the shallow, unconfined aquifer. Historical water level measurements have shown that water levels have fluctuated as much as 5 ft in some areas. The groundwater beneath F.E. Warren AFB is hydraulically connected to the surface water, and discharges into Diamond Creek, Crow Creek, and an unnamed tributary to Crow Creek on Base (U.S.G.S., 1991).

1.3.2 Site Geology

One extraction well and five piezometers were installed at OU 2, Plume C, as shown in Figure 1-2. The wells were continuously logged during their installation, and cross sections of the site geology have been prepared and are shown in Figures 1-3 and 1-4. The geology is very heterogeneous, and the lithology changes over relatively short distances, as indicated by changes between closely spaced piezometers on site. In general, the geology beneath this site consists of silty to gravelly sand at the surface, underlain by clayey sand, a clay lens, and a silty to clayey sand. The clay lens is thickest (17 ft) in the northernmost piezometer (P-5) and thins to the south and east; the clay lens is not present in the eastern piezometer (P-4). The pumping well (EW-1) is 25 ft deep and has a 12-ft screen, whereas the piezometers are about 20 to 25 ft deep, with 15-ft screens. The wells are generally screened across the clay lens with about 5 ft of screen extending into the underlying silty or clayey sand. Exceptions are the northernmost well (P-5), which is screened entirely in the clay unit, and the easternmost well (P-4), which is screened entirely in the clayey sand unit.

Water levels in the piezometers on site range from about 7 to 13 ft bgs and groundwater flow is to the northeast under a gradient of about 41 ft/mile, as shown in Figure 1-5. Groundwater is thought to discharge into Crow Creek, which is located northeast of this site.

1.3.3 Nature and Extent of Contamination

In their remedial investigation from 1987 to 1989 (U.S.G.S., 1991), the U.S. Geological Survey (U.S.G.S.) characterized the nature and extent of contamination at OU 2, Plume C as a TCE plume in the groundwater extending from Buildings 831, 832, and 833 northeastward toward Crow Creek. The TCE is believed to originate from spills and general maintenance activities at or near the buildings. This TCE has contaminated the groundwater at both Fire Training Area 2 and Landfill 7 downgradient (northeast) of the site. Although TCE is the primary contaminant of concern in this plume, additional halogenated VOCs are also associated with this plume, but at

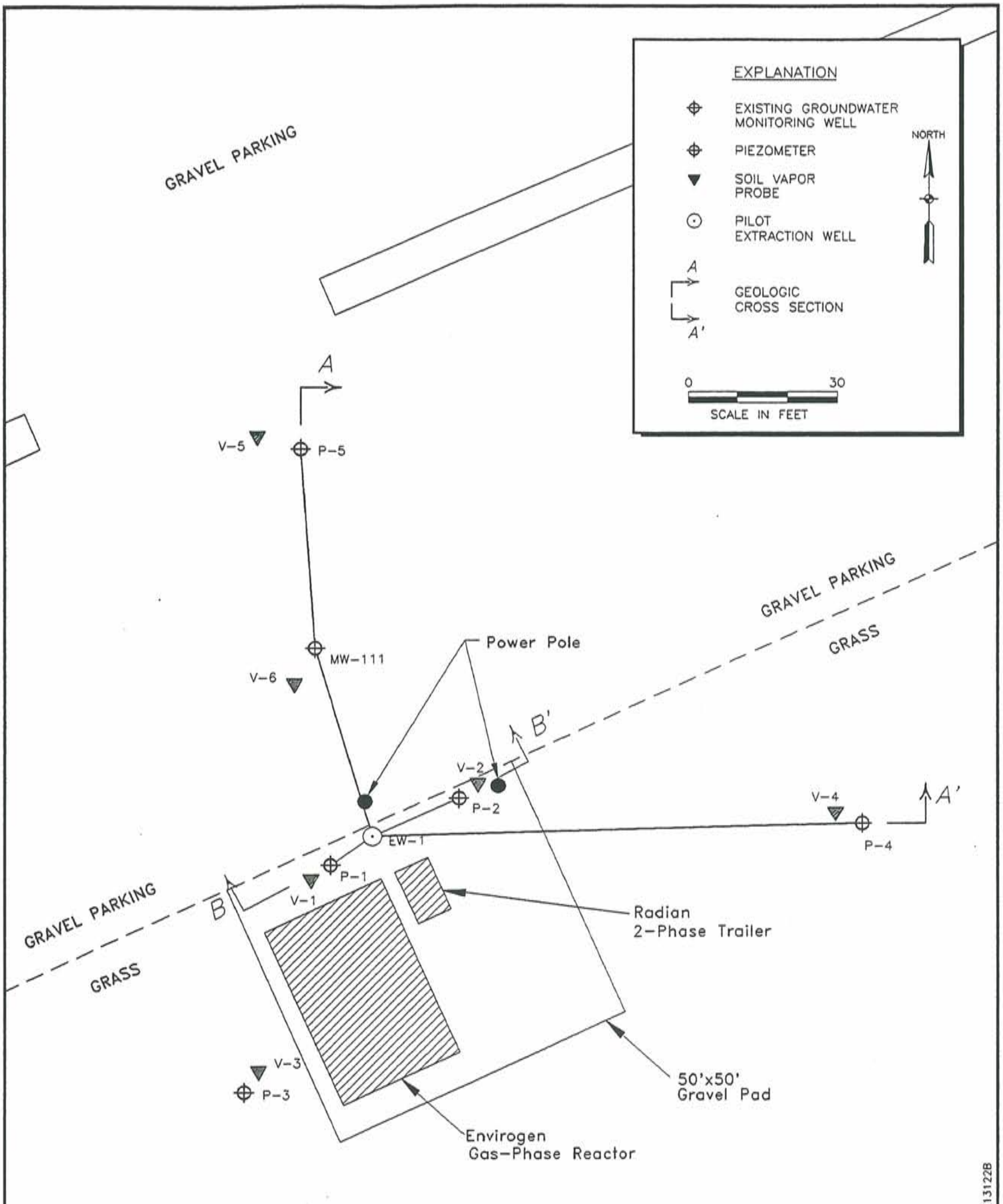

Figure 1-2	**SITE LAYOUT**	
FE WARREN AIR FORCE BASE WYOMING		
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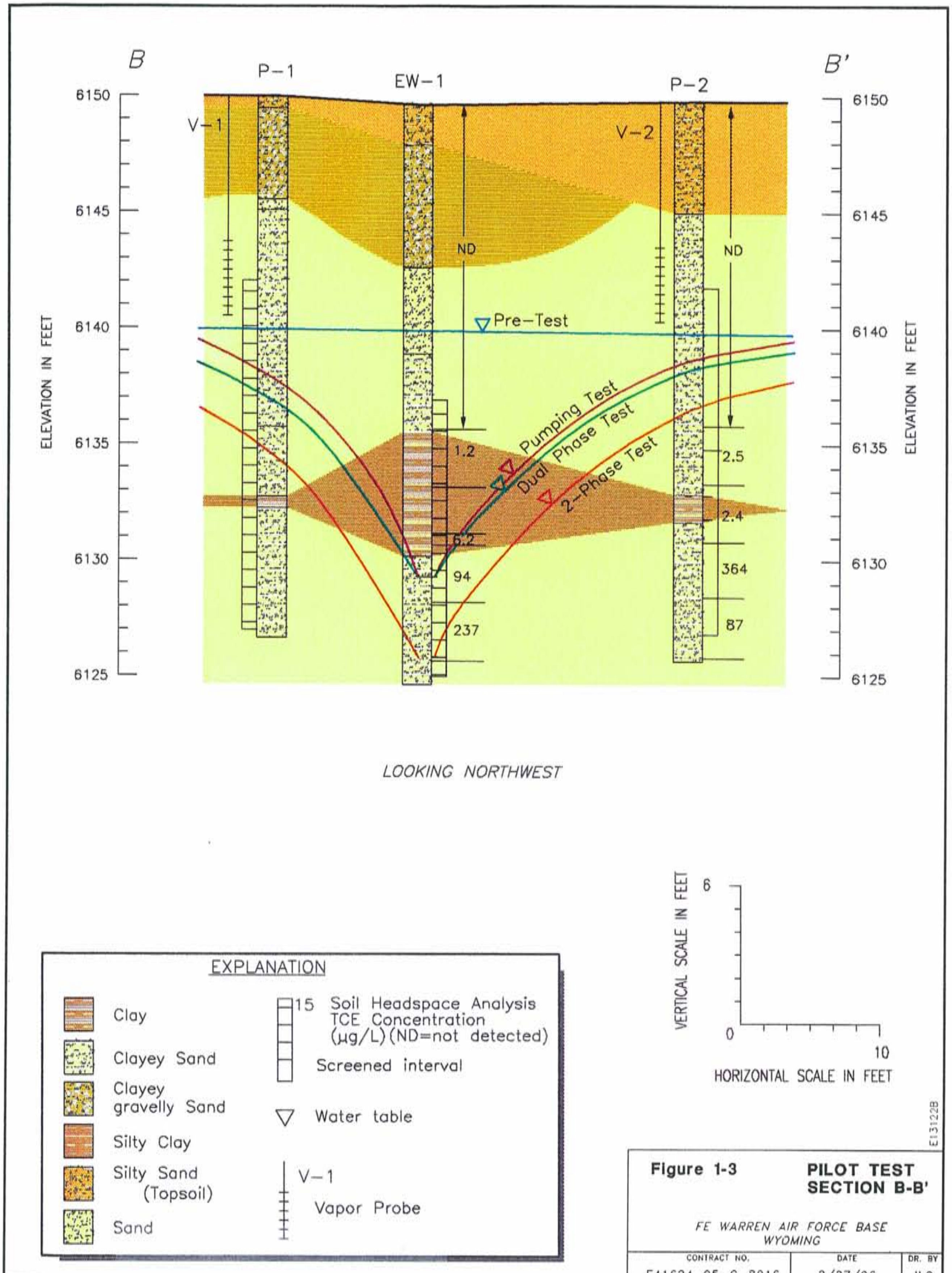

Figure 1-3 **PILOT TEST SECTION B-B'**

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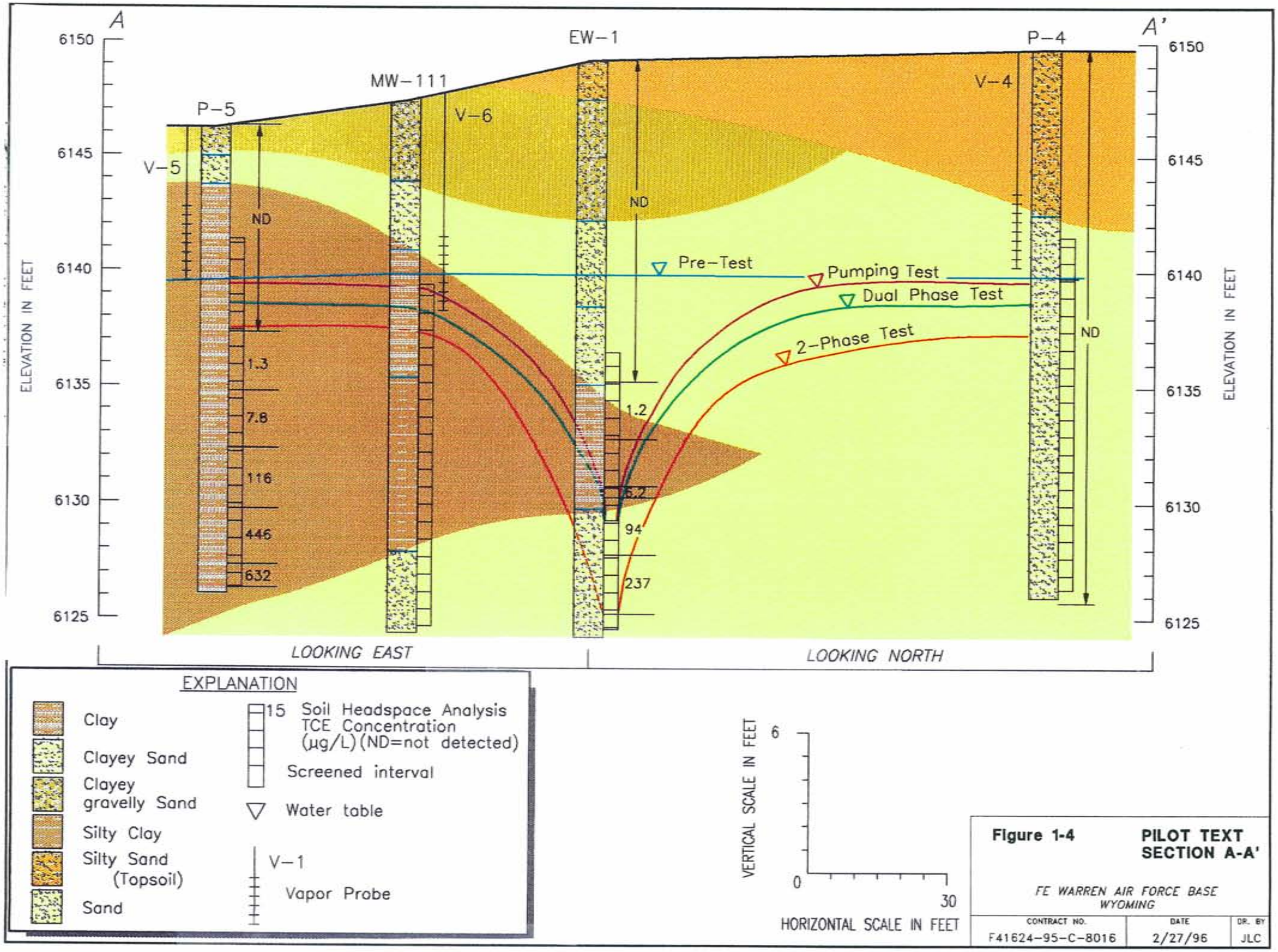

Figure 1-4 PILOT TEXT SECTION A-A'

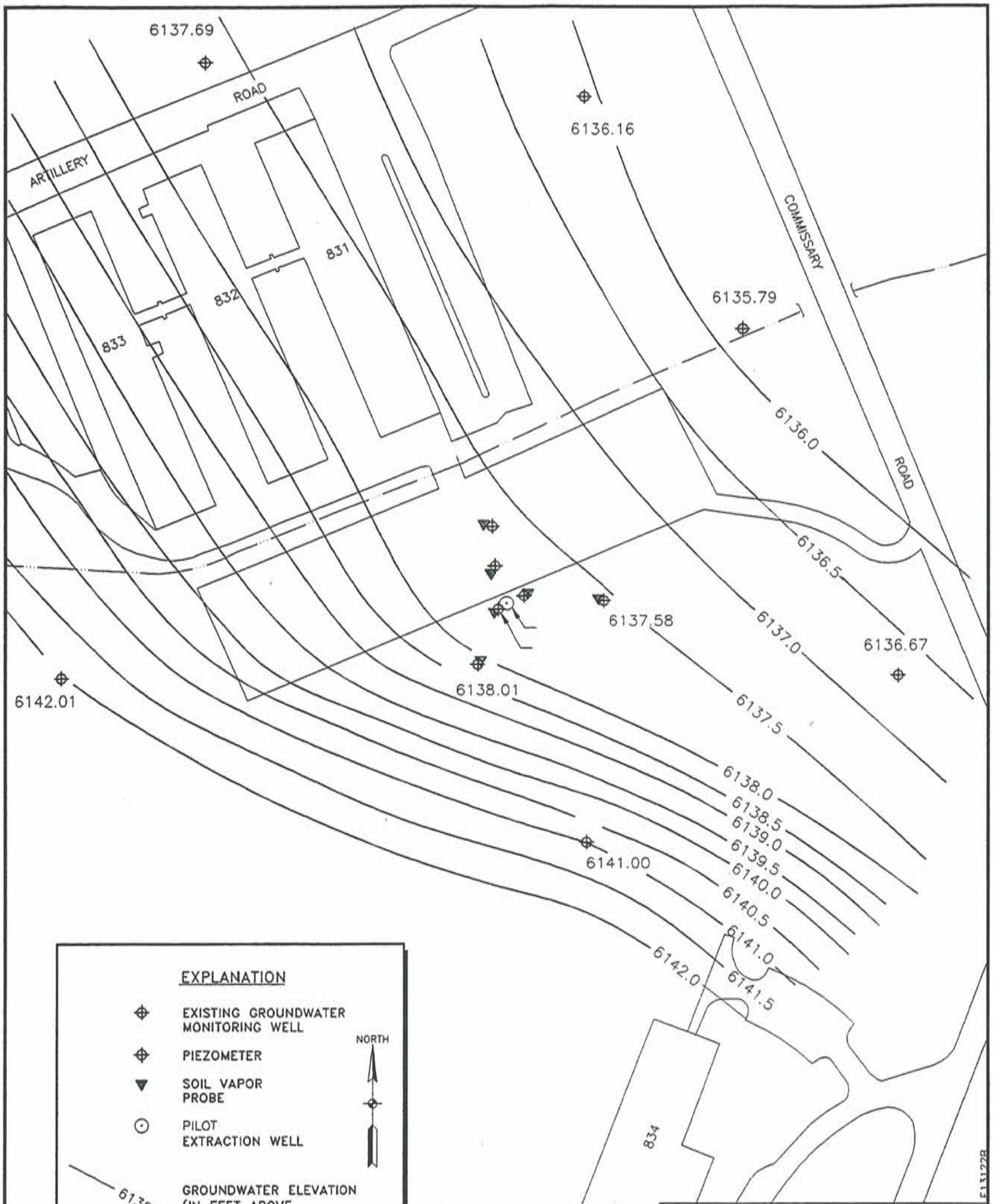

Figure 1-5 PILOT TEST SURROUNDING AREA POST TEST POTENTIOMETRIC SURFACE 1/22/96

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levels substantially lower than the TCE concentrations. TCE concentrations in Plume C measured during the 1987 to 1989 U.S.G.S. investigation ranged from 1 to 7900 μg/L, with the highest concentration detected in MW-111 in July 1989. The 2-Phase test was selected for the area around MW-111 for this reason.

The U.S.G.S. used a portable gas chromatograph/ photoionization detector (GC/PID) to analyze soil cuttings for TCE from the wells drilled on site as part of the current study (Appendix F). The results, summarized in Figures 1-3 and 1-4, indicate that TCE is below detection limits in the unsaturated zone and is first detected at approximately the water table, with concentrations increasing with depth in the wells. This further indicates that all contamination is in the groundwater at this site. No significant TCE was detected in piezometers P-3 and P-4, 60 ft southwest and 100 ft east of the extraction well, respectively.

Section 2
METHODOLOGY

2.1 Site Setup and Operations

The technical approach for the 2-Phase test is presented in this section; however, additional detail is presented in the *2-Phase Vacuum Extraction and Vapor Phase Biotreatment Treatability Study Test Design (TSTD)* document (Radian, 1995a). Details of the sampling and analytical approaches are also presented in that document. This section also provides details on the setup and technical approach of the pump and treat and dual phase extraction tests performed at F. E. Warren AFB. These technologies were added to the test after the TSTD was completed.

2.1.1 Extraction Well, Vapor Probes, and Piezometers

One extraction well (EW-1) and five piezometers (P-1 through P-5) were installed on site for use in this study; one existing monitoring well (MW-111) was also used. Vapor monitoring probes were installed adjacent to each of the piezometers and MW-111. Detailed field notes, lithologic logs, well/vapor probe completion logs, and construction procedures are included in Appendix A.

The wells were installed using the hollow-stem auger drilling method and were extended to a depth of about 20 to 25 ft bgs. The piezometers were constructed of 2-in.-diameter Schedule 40 polyvinyl chloride (PVC) with a 0.01-in. slotted screen in the bottom 15 ft of each well. Three of the piezometers (P-1, P-2, and P-5) have flush surface completions, and two of them (P-3 and P-4) are completed above grade. The pumping well (EW-1) has a flush surface completion and is constructed of 4-in.-diameter Schedule 40 PVC with a 0.01-in. slotted screen in the bottom 12 ft of the well. The existing monitoring well (MW-111) has a flush surface completion, extends to a depth of about 23 ft, and is constructed of 4-in.-diameter PVC screened in the bottom 15 ft.

The vapor probes also were installed using the hollow-stem auger drilling method and were extended to a depth of about 7 to 9 ft bgs. The probes were constructed of 2-in.-diameter Schedule 40 PVC. The bottom 2 to 2.5 ft of each probe is composed of 2-in.-diameter 0.01-in. slotted PVC screen.

2.1.2 Groundwater Pump and Treat

The pump and treat portion of the test was conducted 1-5 October 1995. A Grundfos electric submersible pump was used for the pump and treat portion of the test. The pump was placed in EW-1 and positioned approximately 6 in. from the bottom of the well, and was supported by 1-in.-diameter Schedule 40 galvanized steel discharge piping. An undercurrent sensing device was installed in the power supply circuit of the pump, temporarily stopping the pump if it ran dry. The device was set to allow the pump to automatically restart.

The top of the discharge pipe was fitted with a pressure gauge, a globe valve for throttling water flow, and a totalizing flow meter, which measured water in gallons to an accuracy of 0.1 gal. After water passed through the meter, it was treated in two 55-gal. granulated activated carbon (GAC) canisters arranged in series. Water sampling ports were positioned at the inlet to the first canister, between canisters, and after the second canister.

After the water was treated by the GAC, it was temporarily stored in a 4000-gal. storage tank for testing before being discharged to the sanitary sewer.

The pump and treat test was performed at multiple pumping rates. The first hour of the test was performed at a pumping rate of approximately 2 gallons per minute (gpm). The second hour of the test was performed at a pumping rate of approximately 2.5 gpm. At each pump rate, water level measurements were taken in the extraction well, and the surrounding piezometer wells at 1 to 15 minute intervals.

The remainder of the test was performed at the extraction well's maximum sustainable water flow rate. For extraction well EW-1, this flow rate was approximately 2 gpm.

2.1.3 Dual Phase Extraction

The dual phase extraction technique consisted of pumping groundwater and simultaneously applying a vacuum to the well bore. This portion of the test was conducted 7-18 October 1995. The vacuum was applied to the well from equipment housed in the 2-Phase trailer. Since this equipment produces a higher vacuum than is typically applied in a dual phase mode, the vacuum was throttled back for the first six days of the test. For the second six days, the maximum available vacuum was applied to evaluate the difference in water production rates and mass removal.

A CEE brand, bottom-inlet pneumatic pump was used to pump groundwater from the well, and was powered by a 240-V, 3-phase, 5-hp air compressor connected to the pump by flexible plastic tubing. The pump was a controllerless-style pump that self-regulated its pumping rate depending on the water inflow to the well. Therefore, this style of pump maintains a relatively constant drawdown within the well. The water level within the well was adjusted by the vertical positioning of the pump. The pump was positioned approximately 6 in. from the bottom of EW-1 to maximize water drawdown within the well.

The water flow was measured with a totalizing water meter. (This was the same meter used for the pump and treat test.) Water treatment and discharge were also the same as those used in the pump and treat test. As a check to the water meter, the air supply line to the pump was fitted with a pulse counter. The pulse counter counted the number of pump cycles and, assuming a constant discharge volume, allowed an approximate flow rate to be determined.

The wellhead was fitted with a tee arrangement: vacuum could be applied to one side and water discharged from the other side. The tee was connected to the vacuum source by a 2-in.-diameter flexible hose. As stated above, vacuum was supplied from Radian's mobile 2-Phase trailer; the trailer is described in the *TSTD* (Radian, 1995a).

Vacuum applied to the well was measured by a direct-read dial gauge mounted on the wellhead tee. Vacuum level applied to the well was varied by a butterfly valve mounted in the vacuum piping on the 2-Phase trailer.

Vapors extracted from EW-1 passed through the vacuum pump and were transported to the Envirogen gas-phase reactor system via 2-in.-diameter flexible hose for treatment. The vapor piping on the outlet side of the vacuum pump was fitted with a by-pass tee and valving to regulate the flow to the Envirogen system. Flowmeters were positioned before and after the by-pass arrangement to determine both the total vapor flow from the well and the vapor flow to the Envirogen system.

Vapor samples were extracted from the vapor stream before the by-pass tee, and were analyzed by Envirogen's on-site gas chromatograph (GC).

Well vacuum, vapor flow, and total water produced were periodically recorded during the test. Vapor flow readings were combined with the vapor analysis provided by Envirogen to determine total mass removed in vapor form. Water produc-

tion readings were combined with periodic water analysis results to determine the total mass removed in aqueous form.

Water level readings from the surrounding piezometers and vapor readings from the surrounding vapor points were also taken during the test. These readings provided water radius of influence and vapor radius of influence, respectively.

The dual phase extraction test was performed at two vacuum levels, approximately 16 in. mercury (Hg), and the maximum vacuum the trailer would produce, approximately 23 in. Hg. The two vacuum levels were used to determine the influence of vacuum on mass removal rates, and were based on the equipment capabilities.

2.1.4 2-Phase Extraction

The 2-Phase extraction process removes VOCs and other contaminants in low to moderate permeability subsurface formations. A schematic of the system is shown in Figure 2-1. The process is a modification of conventional vacuum extraction and employs a high-vacuum pump and a small diameter suction pipe (straw) installed into a larger diameter extraction well. The lower end of the straw is set at the desired groundwater drawdown depth, and the wellhead is sealed. To maximize drawdown for this test, the straw was placed 3 in. from the bottom of EW-1. High vacuum (approximately 18 to 26 in. of Hg) is applied to the straw, causing the liquid (groundwater and contaminants) present in the well bore to be aspirated into small droplets by the high velocity flow and become entrained in the vapor being drawn from the well. The vapor consists of soil vapor drawn in from the surrounding formation and, if necessary, air introduced at the wellhead (aspiration air) to enhance liquid entrainment.

Vapor and entrained liquid from the extraction well are conveyed under vacuum up the straw and through a flexible hose toward the vacuum source. The extreme turbulence in the formation, straw, and hose facilities transfers (strips) volatile compounds from the liquid phase to the vapor phase.

The straw size was reduced during the test in an attempt to minimize aspiration air and maximize vapor concentrations sent to the Envirogen gas-phase reactor. Although this resulted in additional head losses in the piping, it successfully achieved a richer mixture and greater flow from the formation.

The wellhead was fitted with two direct read dial vacuum gauges to measure the vacuum at the top of the straw and vacuum in the extraction well bore. The wellhead was also fitted with a vapor flow rotometer to determine the amount of aspiration air entering the well.

Vacuum of 17-25 in. of Hg for this test was supplied by Radian's mobile 2-Phase trailer. The vapor connections from the trailer to the wellhead and to the Envirogen system were the same as those used during the dual phase extraction test. However, during 2-Phase, water and vapor are extracted in the same stream. For the 2-Phase extraction test, water and vapor were separated in the trailer-mounted knock-out pot. Water was pumped from the knock-out pot through the GAC drums and to the sanitary sewer by a positive displacement pump mounted on the trailer. Water flow was measured using a totalizing water meter.

Sampling and readings taken during the 2-Phase test were essentially identical to the dual phase test. These readings were used to determine mass removed in the water and vapor, and radii of influence.

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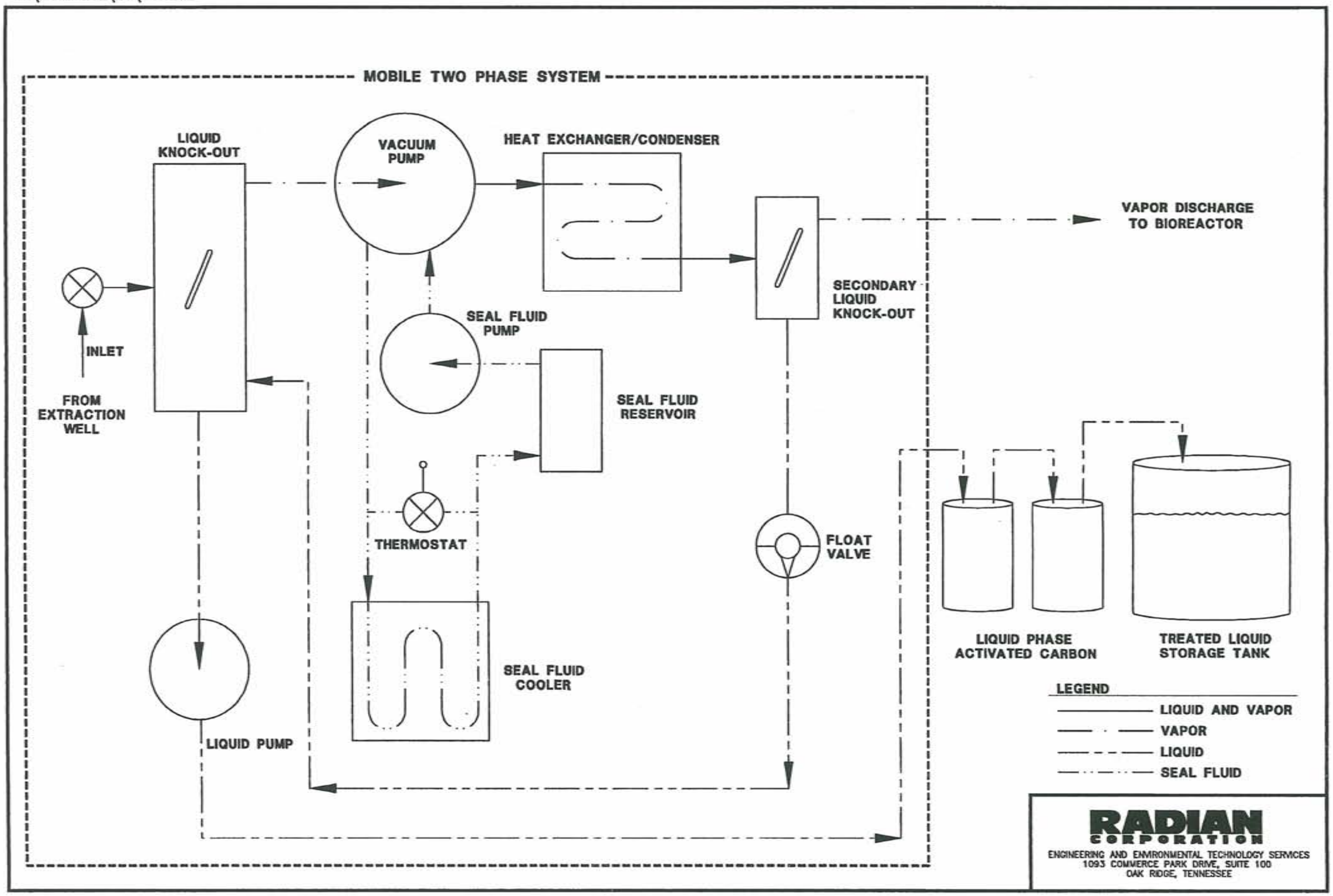

Figure 2-1. 2-Phase Vacuum Extraction Apparatus Schematic

2.1.5 Gas-Phase Reactor

Envirogen's field-pilot bioreactor system contained the bioreactor vessel (TCE Reactor), with automatic pH, foam, and temperature control; a nutrient feed system (basal salts media A and B—BSMA and BSMB); a wastewater transfer skid (Skid 2); and a wastewater holding tank (Waste Holding Tank). A schematic of the gas-phase reactor (GPR) pilot system is shown in Figures 2-2a and 2-2b.

A blower (a component of the TCE Reactor skid) delivered TCE-contaminated vapor from the Radian 2-Phase skid to the bottom of the bioreactor. The vapor was vigorously mixed with the bioreactor's liquid contents, which supported the growth of the degradative bacteria. As the vapor bubbled upward through the liquid column, TCE was transferred from the vapor to the liquid, where it was destroyed by the bacteria. The treated vapor then separated from the liquid at the top of the water column and exited the bioreactor to the atmosphere. Nutrients (BSMA and BSMB) and phenol, a growth substrate for the TCE-degradative bacteria, were metered into the bioreactor with a small volume of make-up water, supplied by Skid 2. The system is capable of handling up to 30 cubic feet per minute (cfm) of air flow, depending on the specific contaminants and concentrations present.

Wastewater from the bioreactor was discharged to the Waste Holding Tank after passing over an overflow weir. The wastewater contained excess biomass and salts that were discharged to the local sanitary water treatment system following TCE, pH, and phenol analysis.

A GC system equipped with an electron capture detector (ECD) and a flame ionization detector (FID) was employed to automatically quantify concentrations of TCE in the influent and treated effluent vapor streams.

During the project, two on-skid (T-101 and T-102) and two off-skid (BSMB and BSMA) chemical feed systems were used to add phenol, caustic, and nutrients to the reactor. The bioreactor pH was automatically controlled with a pH probe. Bioreactor water temperature was controlled through an on-skid heater and refrigeration system. The vapor effluent from the 2-Phase extraction system aftercooler was piped to the GPR system using 2-in.-diameter PVC pipe at the Stream 1 location shown in Figure 2-2a. An off-skid wastewater storage tank, T-104, was used for temporary batch storage of bioreactor wastewater before discharge. A sump to transfer wastewater discharge from the bioreactor to the wastewater holding tank was provided on Skid 2. This skid also contained a transfer pump for supplying make-up water to the GPR system.

The influent vapor flow rate to the bioreactor was measured with a rotometer calibrated to the standard conditions of 17.7 psia and 150°F. The influent vapor pressure and temperature were routinely measured, and the influent flow rate was adjusted to these standard conditions using pressure and temperature correction factors. The effluent vapor flow rate from the bioreactor was measured with an orifice plate calibrated to the standard conditions of 11.6 psia (local atmospheric pressure) and 60°F. No correction factors were applied to the effluent vapor stream flow rate. Typically, the difference between inlet and outlet vapor flow rate measurements was 55% to 70%, owing to pressure differences between the influent and effluent vapor streams.

The operation of Envirogen's GPR system was separated into five tests: (1) abiotic loss test, (2) dual phase extraction test, (3) 2-Phase Extraction test, (4) TCE spiking test, and (5) "killed control" test. A description of the GPR system operation during each of these tests is summarized below. Results of each of these tests are reported in Section 3.

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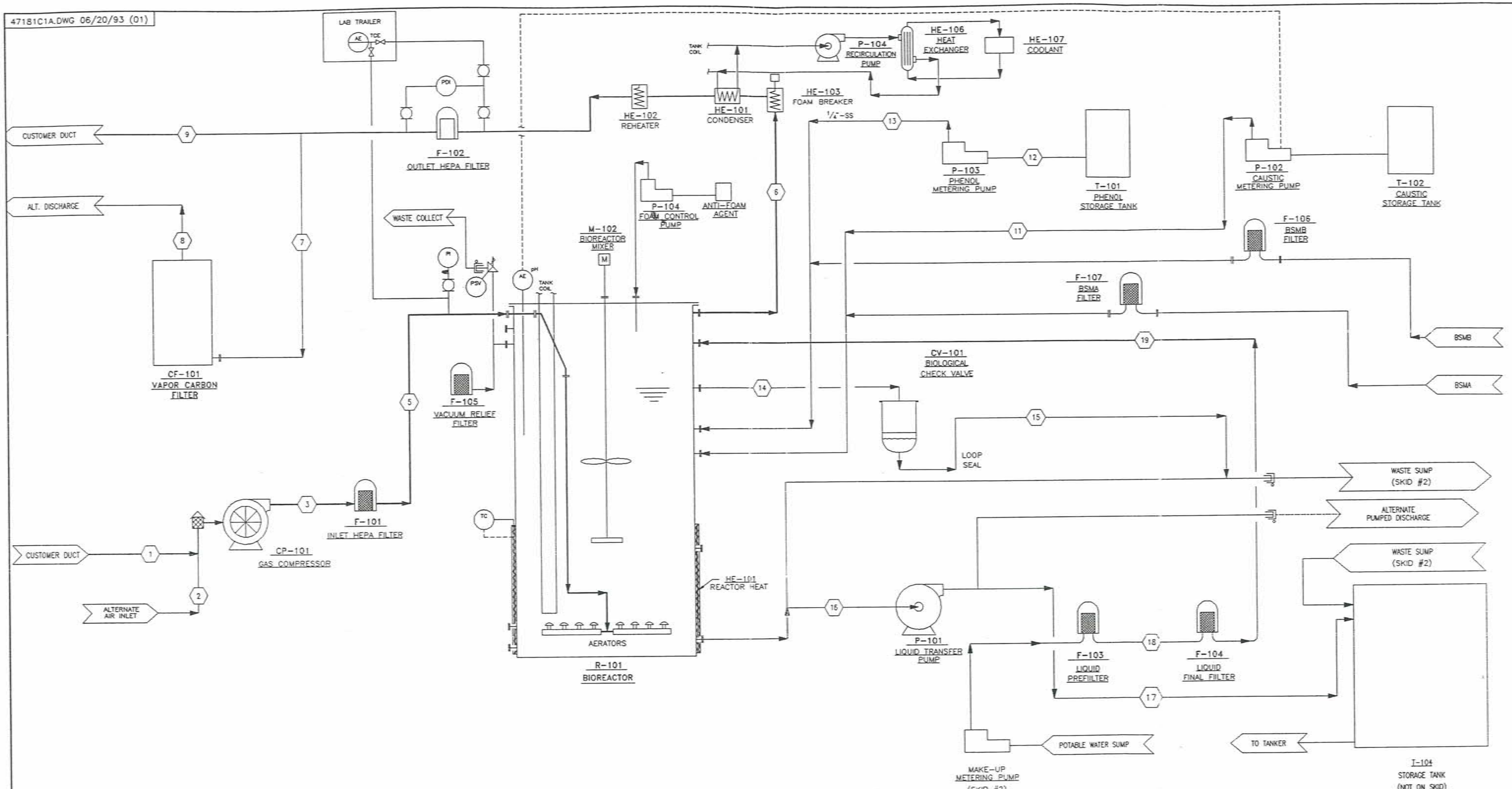

NOTES:

(1) FLOW IS INTERMITTENT
(2) N.A. MEANS NOT APPLICABLE

Figure 2-2a 2-6

STREAM NO. / PARAMETER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
DESIGN FLOW	10 SCFM	10 SCFM	10 SCFM	10 SCFM	10 SCFM	10 SCFM	10 SCFM	10 SCFM	10 SCFM	38 ml/min	38 ml/min	63 ml/min	63 ml/min	38 ml/min	38 ml/min	50 GPM (1)	50 GPM (1)	20 GPM (1)	20 GPM (1)
NORMAL FLOW	4 SCFM	0 SCFM	4 SCFM	0 SCFM	4 SCFM	4 SCFM	4 SCFM	4 SCFM	0 SCFM	—	—	—	—	—	—	50 GPM (1)	20-50 GPM (1)	20 GPM (1)	20 GPM (1)
TCE, mg/l	0.36	0	0.36	0	0.36	—	—	0	—	0	0	0	0	—	—	—	—	0	0
TSS, g/l	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	3.0	3.0	3.0	3.0	0	0
PRESSURE	+1" W.C.	0	5 PSIG	0-5 PSIG	5 PSIG	+4" W.C.	+2" W.C.	0" W.C.	+1" W.C.	0	2 PSIG	0	25 PSIG	+4" W.C.	0	4 PSIG	4 PSIG	19 PSIG	4 PSIG
TEMPERATURE (°F)	70	70	150	70	150	77	85	85	85	60	60	60	60	77	77	60	60	60	60
pH (SU)	N.A. (2)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	—	—	—	—	—	—	—	—	—	—

REV.	DATE	BY	DESCRIPTION	CHK'D	APP'D
A	6/20/95	TEB	ISSUED FOR COMMENTS		

ENVIROGEN
PRINCETON RESEARCH CENTER
4100 QUAKERBRIDGE RD.
LAWRENCEVILLE, N.J. 08648

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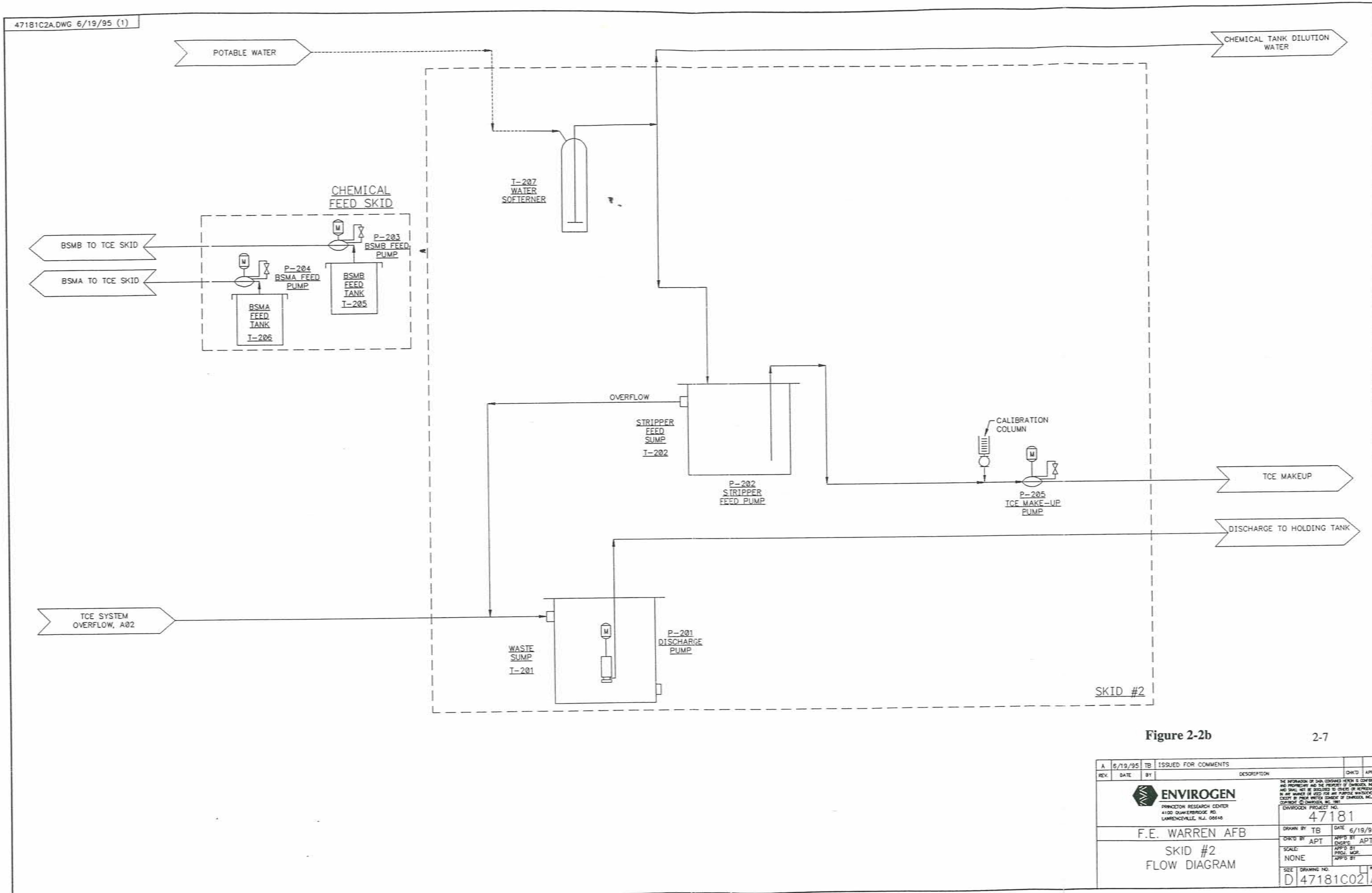
ENVIROGEN PROJECT NO. 47181

F.E. WARREN AFB

TCE VAPOR PHASE PROCESS FLOW DIAGRAM

DRAWN BY TEB | DATE 6/16/95
CHK'D BY APT | APP'D BY ENGR'G. APT
SCALE: NONE | APP'D BY PROJ. MGR. | APP'D BY
SIZE D | DRAWING NO. 47181C01 | X | REV. A



47181C2A.DWG 6/19/95 (1)
POTABLE WATER
CHEMICAL TANK DILUTION WATER
T-207
WATER
SOFTERNER
CHEMICAL
FEED SKID
BSMB TO TCE SKID
BSMA TO TCE SKID
P-203
BSMB FEED
PUMP
P-204
BSMA FEED
PUMP
BSMB
FEED
TANK
T-205
BSMA
FEED
TANK
T-206
OVERFLOW
STRIPPER
FEED
SUMP
T-202
P-202
STRIPPER
FEED PUMP
CALIBRATION
COLUMN
TCE MAKEUP
P-205
TCE MAKE-UP
PUMP
DISCHARGE TO HOLDING TANK
TCE SYSTEM
OVERFLOW, A02
WASTE
SUMP
T-201
P-201
DISCHARGE
PUMP
SKID #2
A 6/19/95 TB ISSUED FOR COMMENTS
REV. DATE BY DESCRIPTION CHK'D APP'D
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REV. A

Figure 2-2b

2.1.5.1 Abiotic Loss Test

Initially, the bioreactor was operated without biomass to ensure that any decreases in TCE observed during subsequent testing periods could be attributed to biological degradation, and not abiotic (nonbiological) processes. Abiotic losses of TCE from the system can occur through adsorption, absorption, or permeation mechanisms. A "TCE spiking system" was used for supplying TCE to the bioreactor during this phase of testing. This spiking system operated by bubbling compressed air at a rate of approximately 0.75 to 0.8 cubic feet per hour (cfh) through TCE contained in a sealed pressure vessel, and mixing this concentrated TCE vapor stream with an ambient air stream supplied to the reactor via the TCE skid blower. During the abiotic loss test, no nutrient salts, phenol, or biomass was added to the water within the bioreactor vessel, and the temperature of the water was not controlled.

The abiotic loss test was conducted over a 50-hour period from 29 September to 1 October 1995. Vapor influent and effluent TCE concentrations were sampled at 1-hour intervals over this period using the on-line GC system and were analyzed via FID.

2.1.5.2 Dual Phase Test

At the end of the abiotic loss test, on 1 October 1995, nutrients, phenol, and TCE-degrading microorganisms were added to the reactor, and the feed pumps were turned on to supply additional nitrogen (N), phosphorus (P), and trace metals, as well as phenol and make-up water to the reactor as the biomass increased in density. The flow rate of ambient air to the system was maintained at approximately 7 to 8 scfm. The pH of the reactor contents during the project was controlled between 7.0 and 7.5, and the temperature was maintained generally between 70° and 90°F.

On 6 October, the biomass density had reached an optical density ($O.D._{550}$) of 0.65 (protein = 0.13 g/L), and the bioreactor was ready to receive TCE vapors. However, vapors from Radian's 2-Phase extraction system were not supplied to the bioreactor until 16 October, after the installation of an "interlock" mechanism designed to protect the bioreactor blower from damage in the event of a 2-Phase system shutdown. In addition, Radian was operating the system in the dual phase mode at this time, and the concentration of TCE in the extracted vapors was very low.

On 16 October, vapors from the extraction system were supplied to the bioreactor at a rate of approximately 4 scfm. By this time, the concentration of TCE in these vapors had increased to between 4 and 7 μg/L. On 18 October, the dual phase test ended.

2.1.5.3 2-Phase Test

On 18 October 1995, Radian began operating the extraction equipment in a 2-Phase mode. The bioreactor was fed vapors from the 2-Phase system until the afternoon of 29 November, at which point the vapor discharge was amended with additional TCE from the TCE spiking system (see below).

2.1.5.4 TCE Spiking Test

After 29 November, the vapor discharge from the 2-Phase system was amended with TCE from the TCE spiking system. The TCE spiking test was conducted over a 13-day period, from 29 November to 12 December 1995. On the third day of the TCE spiking test, an upset condition caused the phenol in the bioreactor to build up, and the TCE removal efficiency dropped from 85% to 60%. The phenol feed was shut off on 2 December to allow the biomass to consume the residual phenol in the reactor. On the following day, after the phenol had been consumed, the phenol feed pump was turned on again. By 4 December, 85% TCE removal efficiency was restored.

Because of extreme cold weather conditions, the extraction system shut down, and problems occurred with the bioreactor over a six-day period from 5 December to 11 December. On 11 December, a break in the weather occurred, the bioreactor system returned to normal operation, and the 2-Phase system was restarted.

2.1.5.5 Killed Control Test

On 14 December, the pH of the reactor contents was raised to approximately 10 in order to significantly decrease the activity of the biomass, and ambient air spiked with TCE was supplied to the system for a period of approximately 24 hours. This "killed control test" was used along with the abiotic loss test to assess the extent of any nonbiological removal of TCE from the system. During the killed control test, no nutrient salts or phenol was added to the bioreactor vessel. Vapor influent and effluent TCE concentrations were sampled at 4-hour intervals over this period using the on-line GC system and were analyzed via ECD. The killed control test was terminated on 15 December.

2.2 Liquid and Vapor Sampling

To assess the effectiveness of the extraction and treatment systems, a number of liquid and vapor samples were collected during the testing period. The sampling and analysis performed during the tests were done in accordance with the *TSTD* (Radian, 1995a) for this project and the existing *Sampling and Analysis Plan and Quality Assurance Project Plan* (U.S.G.S., 1992) prepared for the F.E. Warren AFB Remedial Investigation.

2.2.1 Groundwater Sampling

Groundwater sampling was conducted before, during, and after the pilot study to determine the contaminant levels for mass removal calculations. Samples were also obtained after the extracted groundwater passed through the two drums of liquid GAC to meet the requirements of the effluent discharge permit with the Board of Public Utilities (BPU), Cheyenne, Wyoming. The samples were labeled influent (prior to carbon treatment) or effluent (after carbon treatment). Pretest groundwater samples were obtained from the extraction well (EW-1) on 11 September 1995, and a posttest groundwater sample of EW-1 was obtained on 15 December 1995. During both the pump and treat test and the dual phase test, seven groundwater samples were collected. During the 2-Phase test, seven groundwater samples were collected after 2-Phase extraction but prior to carbon treatment (influent); five samples were collected after carbon treatment prior to discharge (effluent).

2.2.2 Vapor Sampling

During the dual phase and 2-Phase tests, Envirogen analyzed all vapor streams with an SRI Model 8610 GC. The GC was cycled to pull four samples per day. For each GC run, the following four vapor streams were sampled in the following order: (1) ambient air, (2) bioreactor effluent, (3) bioreactor influent, and (4) 2-Phase extraction system effluent. Samples were drawn through Teflon® tubing connected to these four points. All sample readings were averaged each day to obtain the mean concentration of vapors coming from the subsurface.

2.2.3 Gas-Phase Reactor Biomass Sampling

The bioreactor was equipped with a sample port on the side of the vessel that was used for sampling the reactor contents. When required, between 300 and 500 mL of liquid was removed manually for analysis of biomass density, pH, phenol concentration, nitrogen, phosphorus, and biological activity.

The wastewater storage tank was also equipped with a sample port at the bottom of the vessel. Samples of the liquid within the storage tank were analyzed for phenol, TCE, and pH before discharge to the sanitary sewer.

2.3 Analytical Procedures

Groundwater and treated effluent samples that were obtained before, during, and after the test were forwarded either to the Quanterra, Inc. laboratory (Arvada, Colorado) or the U.S.G.S. field laboratory. The following sections present the methodology used at both laboratories. All vapor samples were analyzed by Envirogen.

2.3.1 Water Analytical Procedure

Influent water samples were obtained prior to carbon treatment. Effluent discharge samples were also obtained immediately after carbon treatment to satisfy the requirements of the BPU discharge permit and to identify carbon breakthrough. U.S.G.S. personnel collected field samples of both the influent and effluent discharges for same-day turnaround. Radian personnel collected regular samples of the influent and effluent discharge and shipped them to the Quanterra laboratory for both expedited one-day and the standard turnaround analytical procedures.

2.3.1.1 U.S.G.S./Field Screening

The U.S.G.S. provided analytical support to field screen the water samples at the direction of the F.E. Warren AFB environmental flight restoration program manager. The samples were obtained in 40-mL volatile organic analysis (VOA) vials and taken directly to the U.S.G.S. field laboratory for GC analysis. The U.S.G.S. operates a portable GC (Photovac) according to the procedures outlined in the F.E. Warren AFB *General Sampling and Analysis Plan and Quality Assurance Project Plan* (U.S.G.S., 1992).

The analysis was provided to Radian by the end of each day a sample was taken. This information was reported to the restoration project manager every 10 days. The 10-day reporting was required by the BPU permit granted to F.E. Warren AFB for this test (Appendix B).

2.3.1.2 Laboratory Analyses

Quanterra, Inc. laboratory analyzed groundwater samples for VOCs using EPA Method 524.2 in accordance with the existing F.E. Warren AFB *Sampling and Analysis Plan* (U.S.G.S., 1992). Quanterra noted that standard analytical protocols were followed in the analysis of the samples. Quanterra reported that all laboratory QC samples analyzed in conjunction with the samples in the test were within established control limits. Radian delivered influent and effluent samples to Quanterra for analysis throughout the test.

Quanterra also analyzed water samples from the Envirogen GPR effluent holding tank prior to discharge. The water was analyzed for phenols and TCE.

2.3.2 Vapor Analytical Procedure

The GPR and the 2-Phase extraction systems were monitored with an SRI Model 8610 GC equipped with an ECD and FID in series for analysis of vapor-phase TCE concentrations. An average of four GC runs was performed each day.

During the abiotic loss test, TCE concentrations were obtained using the FID calibration curve. Two check standards were run during the abiotic loss test to confirm the validity of the FID calibration curve. Because of the lower than expected TCE concentrations discharged from the vapor extraction system, TCE concentrations during the remainder of the test were obtained using the ECD calibration curve.

2.3.3 Gas-Phase Reactor Liquids Analytical Procedure

Minor corrections in important GPR system operating parameters were periodically made in order to maintain and/or optimize GPR system performance. Information from field assays conducted on the bioreactor contents was used to make these corrections. The field assays were (1) biosolids, (2) phenol, (3) ammonia nitrogen and orthophosphate, (4) phenol-specific activity, and

(5) TCE-specific activity. The biosolids and phenol concentrations were monitored daily, whereas the ammonia and orthophosphate concentrations were analyzed approximately twice each week. The phenol-specific activity was analyzed on a weekly basis, and the TCE-specific activity was analyzed every one to two weeks. Colorimetric methods were used for the field assays.

Samples of the reactor contents were also periodically sent to Envirogen for analysis of total Kjeldahl nitrogen (TKN) (EPA Method 351.3), phosphorous (EPA Method 365.2), total organic carbon (TOC) (EPA Method 415.1), total suspended solids (TSS) (EPA Method 160.2), and base neutrals (EPA Method 625).

The liquid within the wastewater holding tank was also analyzed daily for phenol using the field assay analysis. A sample of the liquid was analyzed for TCE by U.S.G.S. before discharge. To confirm the field analyses prior to discharge, a sample of the liquid within the holding tank was also sent to Quanterra for phenol and TCE analysis.

Section 3
RESULTS

This section presents the results of the field measurements and analyses performed during the test. Each of the three portions of the test (pump and treat, dual phase, and 2-Phase) is discussed separately, along with the gas-phase reactor and aquifer testing results.

Water and vapor flow rates from the extraction well for all three portions of the test are shown in Figures 3-1 and 3-2, respectively. Changes in the piezometer water levels during the test are shown in Figure 3-3. The majority of the water extracted during the test probably originated from the silty to clayey sand, with a relatively small amount of water generated from the overlying clay unit (See Figures 1-3 and 1-4).

A total of about 1.5 lb of TCE was removed from the formation during the test. Table 3-1 is a summary of TCE removed during the three portions of the test. Figure 3-4 shows the daily TCE mass removal rate throughout the test.

Table 3-1
TCE Removal

Test	Oper. Days	lb TCE Water	% of Total	lb TCE Vapor	% of Total	Total lb TCE	Gal Water	Total lb/gal	Total lb/day
Pump &Treat	5	0.055	100	0	0	0.055	11844	4.7×10^{-6}	0.011
Dual Phase	12	0.118	88	0.016	12	0.134	52837	2.5×10^{-6}	0.011
2-Phase	47	0.021	1.6	1.331	98.4	1.352	169883	8.0×10^{-6}	0.029

A summary of field measurements, analytical results, and mass removal calculations is presented in Appendix C. Laboratory reports are included in Appendix D.

3.1 Pump and Treat Test

3.1.1 Groundwater Production/Radius of Influence

The water production rate during the 5-day pump and treat test ranged from about 2 to 3 gal. per minute (gpm). On the basis of the water level drawdowns shown in Figure 3-3 and the potentiometric surface (shown in Figure 3-5), the radius of influence is estimated to be approximately 100 ft. The drawdown cone is somewhat asymmetrical, as shown in Figure 3-5.

The water discharge rate decreased over the test period from about 3 to 1.9 gpm. The drawdown in the pumping well (EW-1) during the pump and treat test was approximately 9 ft (20 ft bgs), which is about 1 ft below the clay layer, in the underlying clayey sand.

3.1.2 Mass Removal

A total of 0.055 lb (0.011 lb/day) TCE was removed during the pump and treat test, as shown

Figure 3-1
Water Flow Rate and Well Head Vacuum

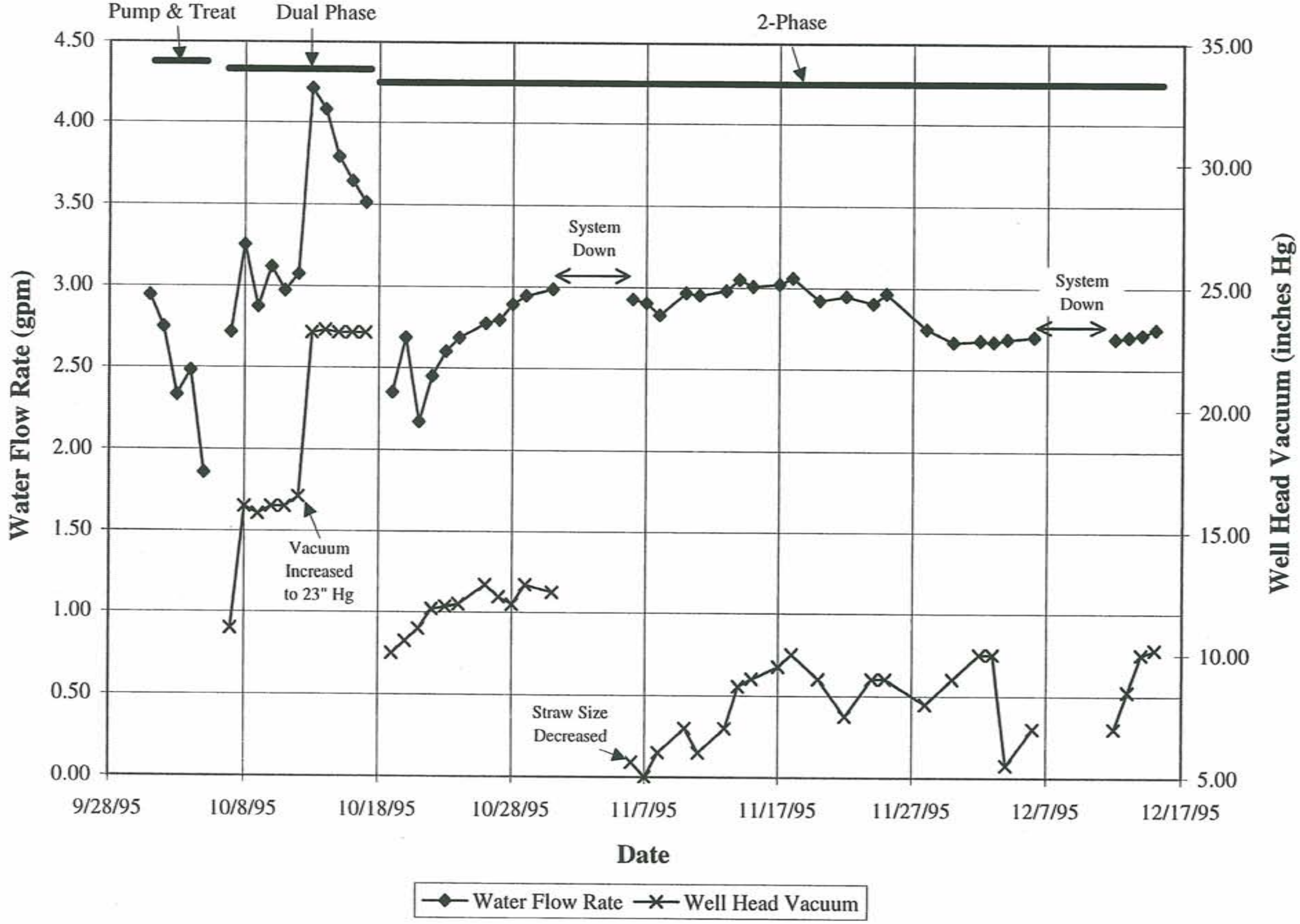


Figure 3-2
Vapor Flow Rate and Well Head Vacuum

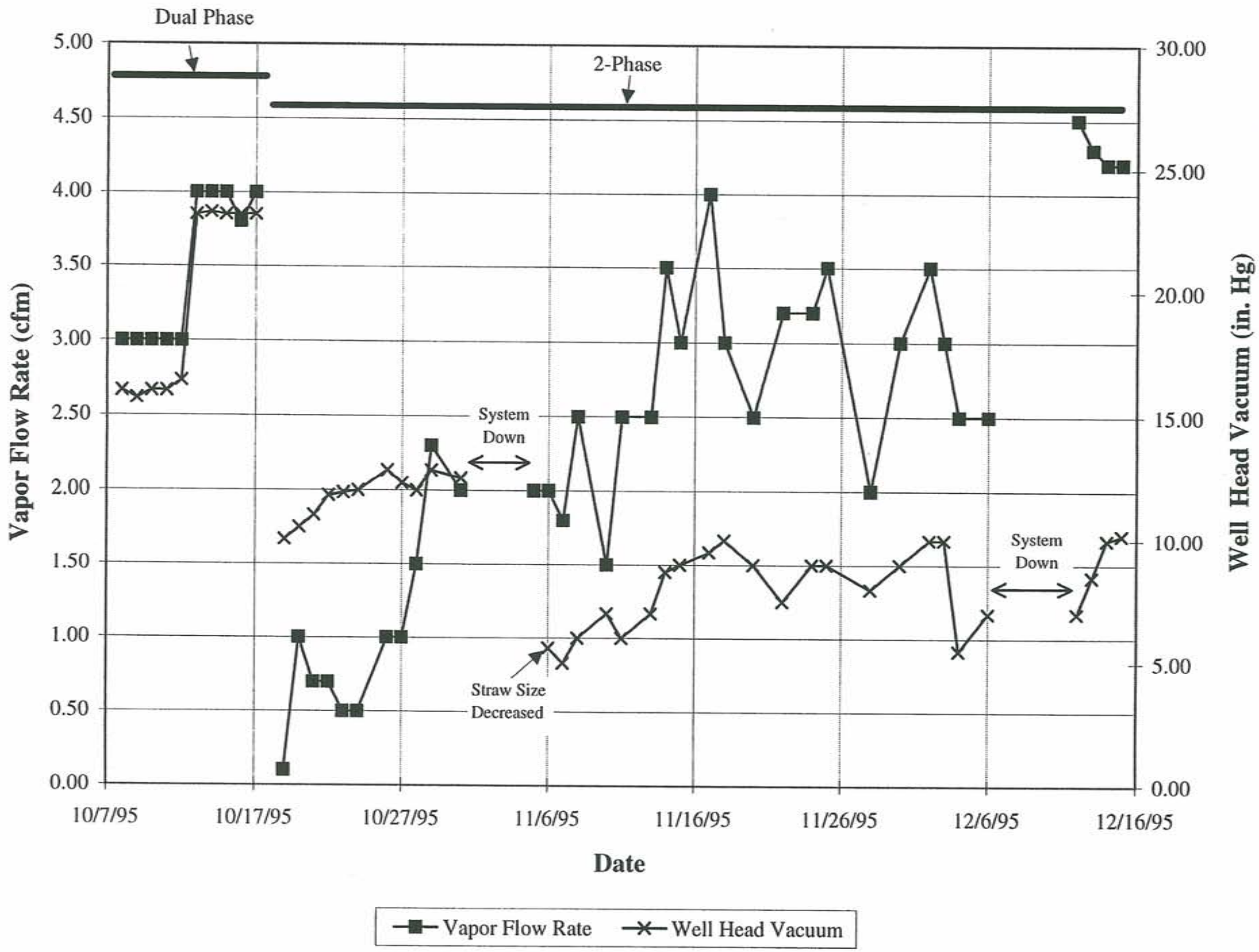


Figure 3-3
Change in Water Levels over Time

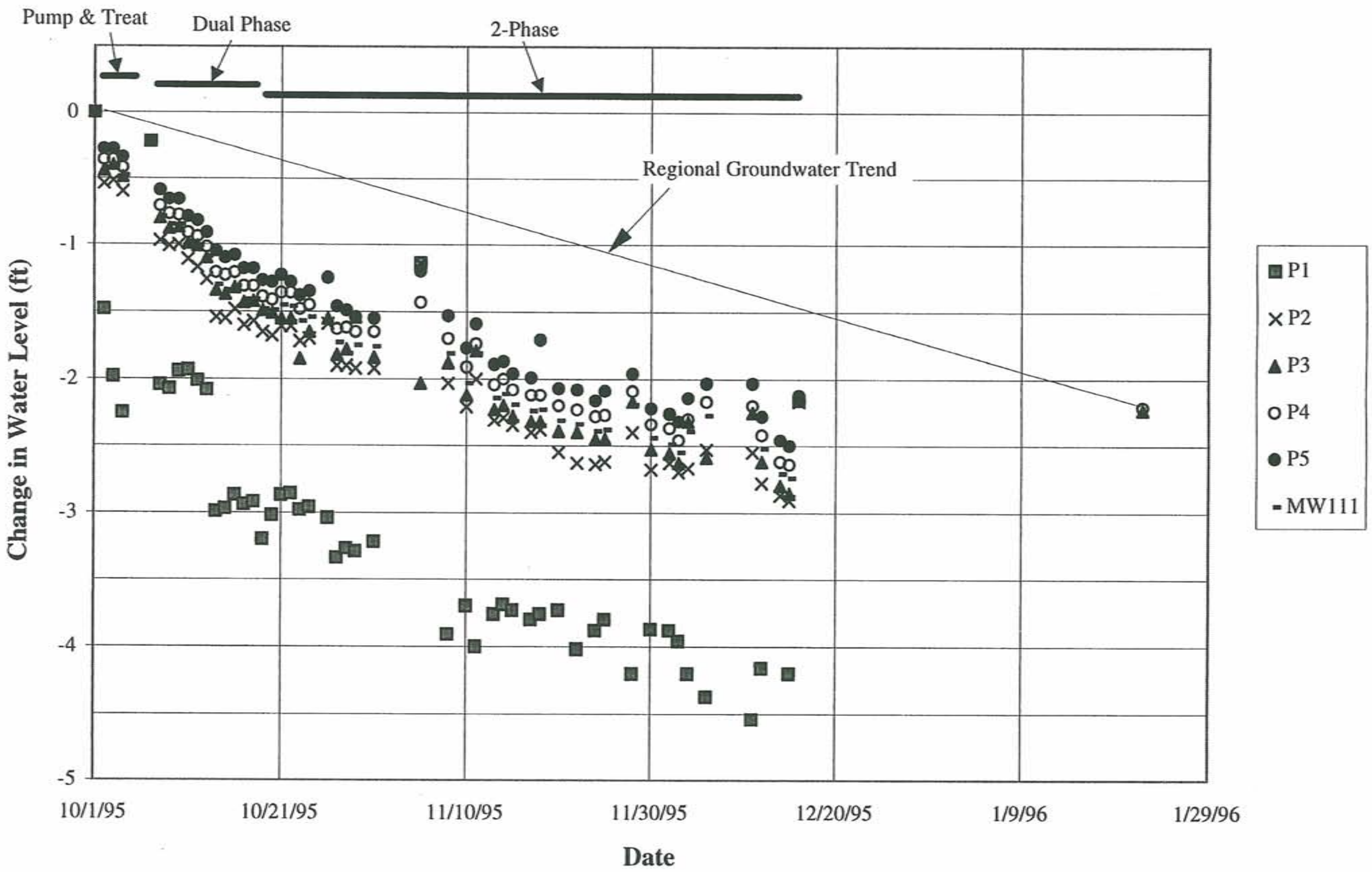
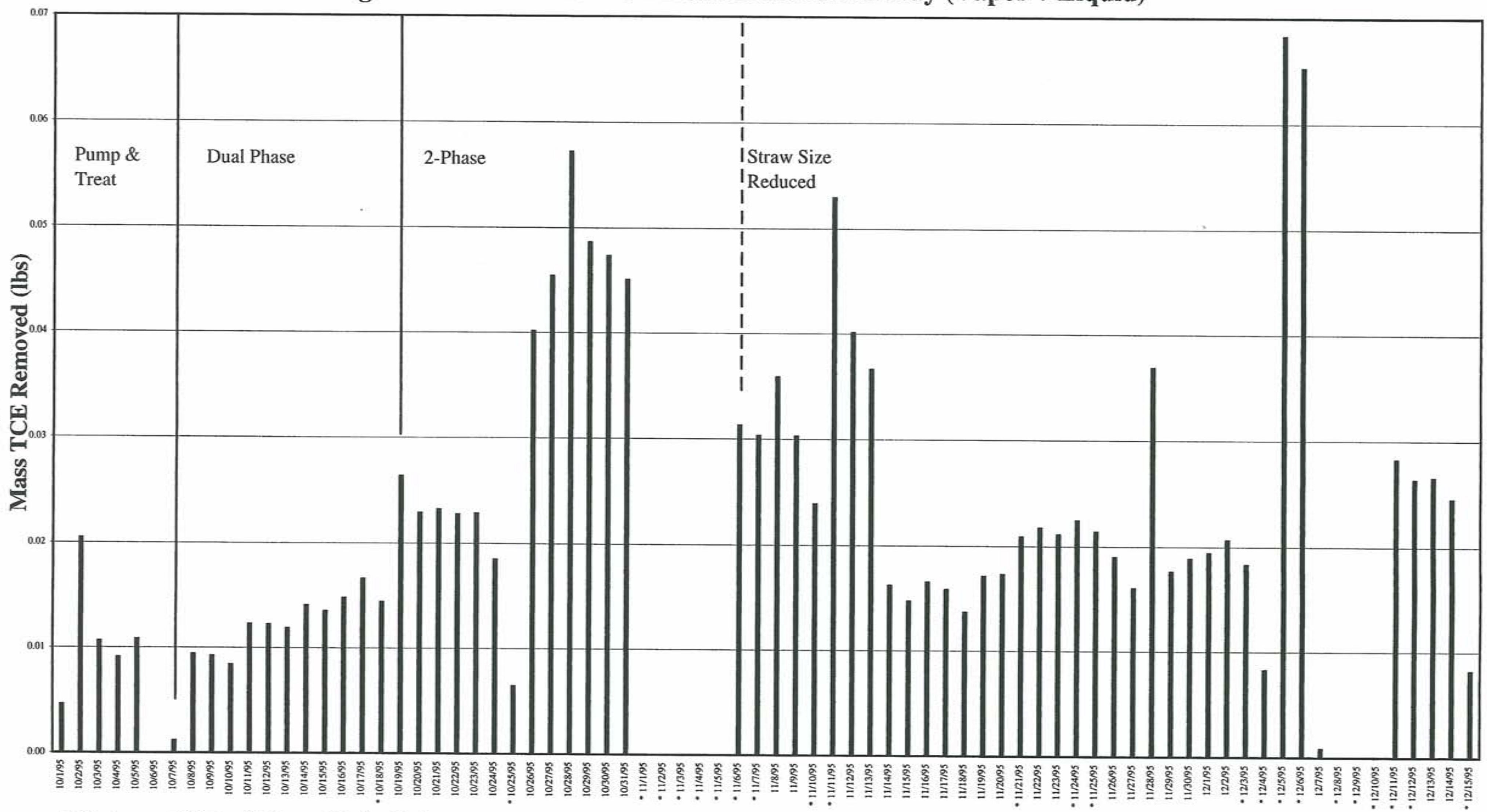


Figure 3-4. Extracted TCE Mass Removal Per Day (Vapor + Liquid)



* System partially/totally inoperable for this date

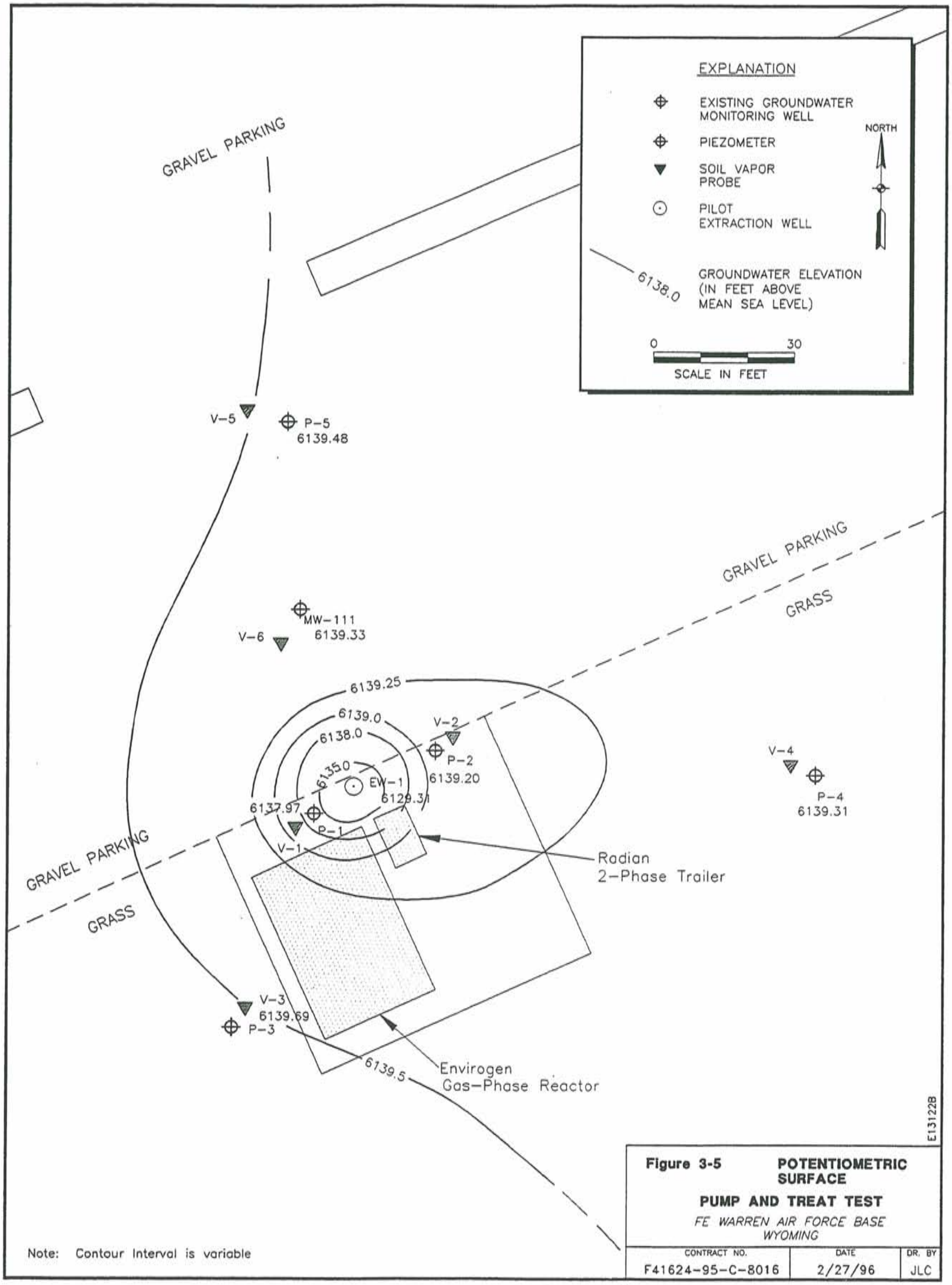


Figure 3-5 POTENTIOMETRIC SURFACE
PUMP AND TREAT TEST
FE WARREN AIR FORCE BASE WYOMING

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in Table 3-1. The mass removal results per day are shown in Figure 3-4. The first day of the test was a partial day, with the beginning of the test performed at reduced pumping rates; therefore, mass removal for the first day is low. The remainder of the test was performed at maximum pumping rate, with TCE concentrations in the water remaining fairly constant throughout the test. Day 2 produced the most water, resulting in the highest daily mass removal. The results are typical of a pump and treat test.

Pre-test groundwater TCE concentration in EW-1 (immediately after well installation) was 36 μg/L. Concentrations during the test ranged from 250 to 1,000 μg/L

3.2 Dual Phase Test

3.2.1 Groundwater Production/Radius of Influence

The water production rate during the 12-day dual phase test was about 3 gpm during the first half of the test under a vacuum of 16 in. of Hg. Midway through the test, the well vacuum was increased to 23 in. Hg and water production increased to about 4 gpm. On the basis of the water level drawdowns shown in Figure 3-3 and the potentiometric surface, the radius of influence is estimated to be approximately 100 ft. The drawdown cone is asymmetrical, as shown on the potentiometric surface map from the end of the dual phase test (Figure 3-6). The drawdown in the pumping well (EW-1) during the dual phase test was approximately the same as the drawdown observed during the pump and treat test.

3.2.2 Vapor Production/Vacuum Influence

Vapor flow rates during the dual phase test ranged from 3 to 4 cfm. The well vacuum was approximately 16 in. Hg for the first half of the test, corresponding to a vapor flow rate of 3 cfm. After the well head vacuum was increased to 23 in. Hg, the vapor flow rate increased to 4 cfm (Figure 3-2).

Vacuum readings from the vapor probes showed little measurable vacuum during the dual phase test, with vacuum readings in the probes ranging from 0 to 0.21 in. of water. Figure 3-7 shows the vapor probe vacuum measurements over time. No vacuum was recorded until the wellhead vacuum was increased from 16 to 23 in. Hg.

These low vacuum readings are probably attributable to the tight clay soils beneath the site. Almost all of the extraction well screen was in or below a clay lens in the saturated zone, which may have limited the vacuum influence in the overlying vadose zone where the probes were located.

3.2.3 Mass Removal

A total of 0.134 lb (0.011 lb/day) TCE was removed during the dual phase test, as shown in Table 3-1. The removal rate was similar to that obtained during pump and treat. The mass removal results per day are shown in Figure 3-4. Mass removal rates increased slightly with the increased vacuum applied midway through the test, because of increased water and vapor flow rates. Overall, 88% of the TCE mass was removed in the aqueous phase, and 12% in the vapor phase.

TCE concentrations in groundwater during the test ranged from 200 to 448 μg/L

3.2.4 Gas-Phase Reactor Treatment

At the end of the dual phase test, the bioreactor was fed vapors from Radian's extraction system for a period of two days. During this time, the concentration of TCE in the extracted vapors was 4 to 7 μg/L (less than 0.002 lb per hour of TCE load), and the TCE removal efficiency was greater than 95%. Calculations are shown in Appendix G.

Table 3-2 below shows the operating parameters of the GPR system during the dual phase test.

Table 3-2
GPR Operating Parameters During the Dual Phase Test (10/16/95-10/18/95)

Operating Parameter	Range During Dual Phase Test
pH	7.0 to 7.5
Reactor Temperature (°F)	75 to 80
Biomass Density ($O.D._{550}$)	1.0 to 2.1
Make-up Water Rate (gpd[+])	60 to 70
Inlet Vapor Flowrate (scfm)*	4.0 to 4.2
Inlet TCE Conc. Range (μg/L)*	4 to 7

[+]calculated from pump settings
*standard conditions = 14.7 psia and 77°F

3.3 2-Phase Test

3.3.1 Groundwater Production/Radius of Influence

The water production rate during the two-month 2-Phase test slowly increased from about 2.4 gpm and then stabilized at about 3 gpm after 10 days of operation. After a shutdown to change straw size, water flow rates remained around 3 gpm for 15 days, then gradually decreased to about 2.7 gpm for the remainder of the test. Based on the water level drawdowns shown in Figure 3-3 and the potentiometric surface at the end of the test (Figure 3-8), the radius of influence is estimated to be approximately 100 ft.

Significantly greater drawdown was obtained in the 2-Phase test than in the other tests (approximately 14 ft). This is primarily because the extraction straw was placed at the bottom of the well, which dewaters the entire well, whereas the other methods require that the pump be submerged.

3.3.2 Vapor Production/Vacuum Influence

Vapor flow rates from the formation during the 2-Phase test ranged from about 0.5 to 6.0 scfm. The well head vacuum was approximately 9-13 in. Hg and generally increased over the duration of the test. Total flow, including aspiration air, was approximately 5-11 scfm.

Vapor flow rates slowly increased during most of the test as the formation was slowly dewatered. Flow rates also increased after the straw diameter was decreased on 5 November (Figure 3-2), resulting in a decrease in aspiration air. Vapor flow rates remained generally in the 2 to 4 scfm range for the duration of the 2-Phase test, following the change in straw size. The increase to 4-6 scfm at the end of the test resulted from supressing the aspiration air. This was not done earlier in the test because of limited vapor flow produced and the resulting stress on the pump.

Readings from the vapor probes during the 2-Phase test showed little measurable vacuum throughout the test, ranging from 0 to 0.12 in. of

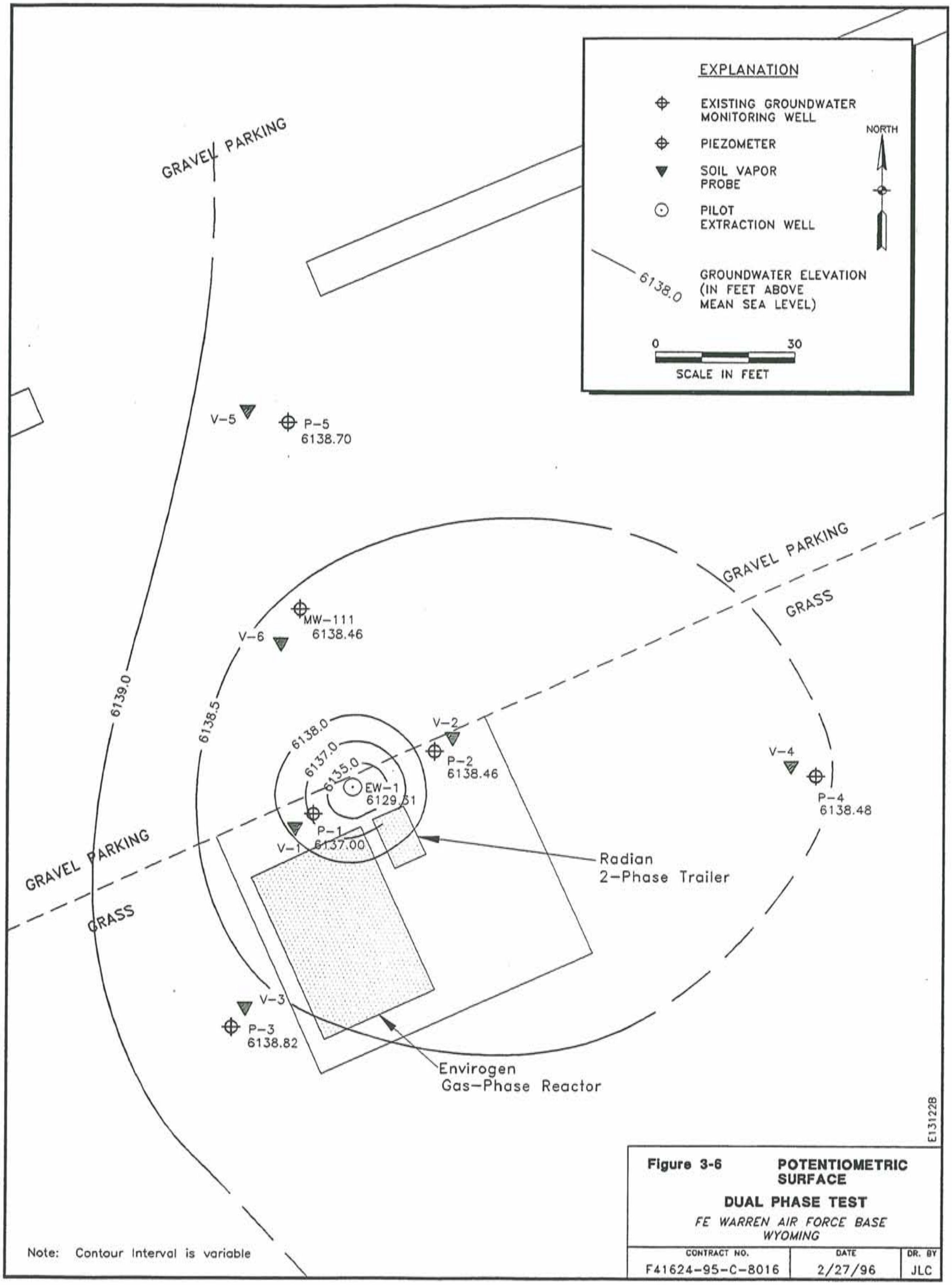

Figure 3-6 **POTENTIOMETRIC SURFACE**

DUAL PHASE TEST

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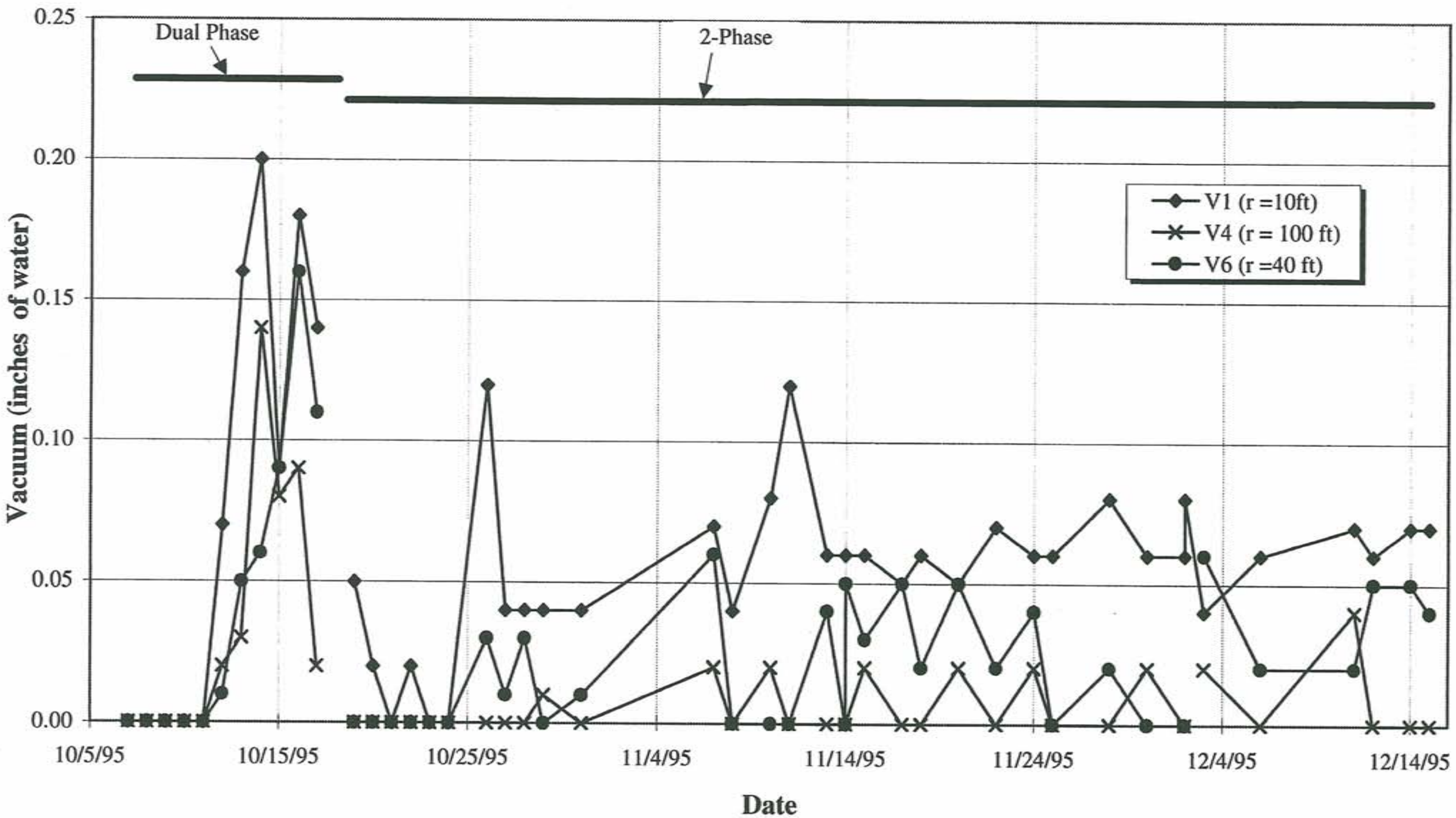
Figure 3-7
Vapor Probe Vacuum Readings[a]



[a]Vapor probe data shown is representative for the site. Vacuum readings for V-2, V-3, and V-5 are included in the appendices to this report.
r = Distance from pumping well EW-1

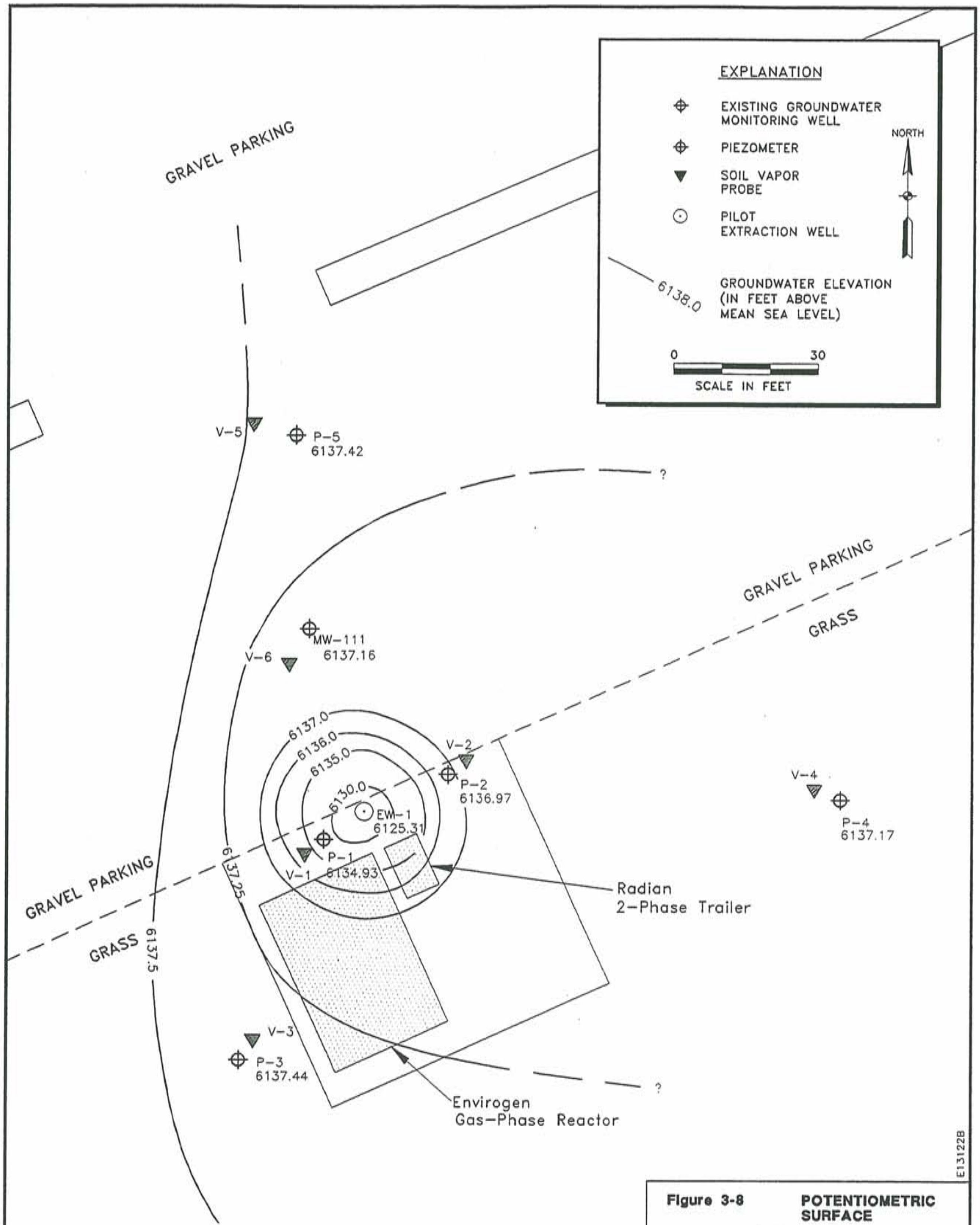


Figure 3-8 **POTENTIOMETRIC SURFACE**

2-PHASE TEST

FE WARREN AIR FORCE BASE WYOMING

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water, as discussed in Section 3.2.2. Figure 3-7 shows the vapor probe vacuum measurements over time.

3.3.3 Mass Removal

A total of 1.352 lb (0.029 lb/day) TCE was removed during the 2-Phase test, as shown in Table 3-1. The removal rate was approximately 2-3 times the rates obtained during pump and treat and dual phase.

Severe cold weather conditions at the site caused freezing of the extracted water in the interconnecting piping, resulting in two unscheduled shutdowns of the test. The shutdowns occurred from 1-5 November 1995 and 7-10 December 1995. Minor shutdowns also occurred on parts of several other days.

The 2-Phase process, similar to the dual phase process, simultaneously removes water and vapor from the subsurface. The method of water and vapor removal is different between the two processes, and 2-Phase extraction usually transfers or strips most of the VOC mass in the aqueous phase to the vapor phase.

The mass removed per day in the aqueous phase is shown in Figure 3-9. The first part of the test was run with a 1.25-in.-diameter straw, and the TCE concentration in water was slightly higher during this period. The remainder of the test (starting 6 November) was performed with a 1-in.-diameter straw, possibly promoting more stripping action to the water. The mass removed the day after the first shutdown (11/6) was higher than average, due to high TCE concentrations in the water rather than high water production. Overall, TCE mass removal in the aqueous phase represented 1.6% of the total TCE mass removed by 2-Phase.

The mass removed per day in the vapor phase is shown in Figure 3-10. The first seven days of the test produced low mass removal rates followed by increasing removal rates. The most reasonable explanation for this is that additional subsurface area was exposed because of the higher water drawdown during 2-Phase extraction, and this area slowly developed vapor flow as it dewatered. The remainder of the test produced fairly constant mass removal, except for the last several days of the test. An effort was made to maximize the subsurface vapor flow by minimizing the aspiration air flow during this time period. This produced slightly higher mass removal rates. This type of operation is stressful on the extraction equipment and was therefore done for a limited time period.

The TCE mass removal in the vapor phase represented 98.4% of the total TCE mass removed by 2-Phase.

The post-test TCE concentration in the groundwater was 150 μg/L.

3.3.4 Gas-Phase Reactor Treatment

Figures 3-11 (a and b) and 3-12 show the daily bioreactor TCE load and removal efficiency, respectively, during the project. Day "1" corresponds to 6 October 1995, the day after the biomass growth start-up period. During the 2-Phase test, the daily TCE removal efficiency averaged 90% (including any abiotic losses). The total amount of TCE processed through the bioreactor during the 2-Phase test was 0.93 lb, and approximately 90% (0.83 lb) of this TCE was removed.

U.S.G.S. analyzed the TCE concentration of the bioreactor discharge water five times during the 2-Phase test; each time, no TCE was detected.

On the basis of the results above, a total TCE mass balance around the reactor during the 2-Phase test yielded the following results:

Figure 3-9. Two Phase TCE Mass Removal Per Day (Water)

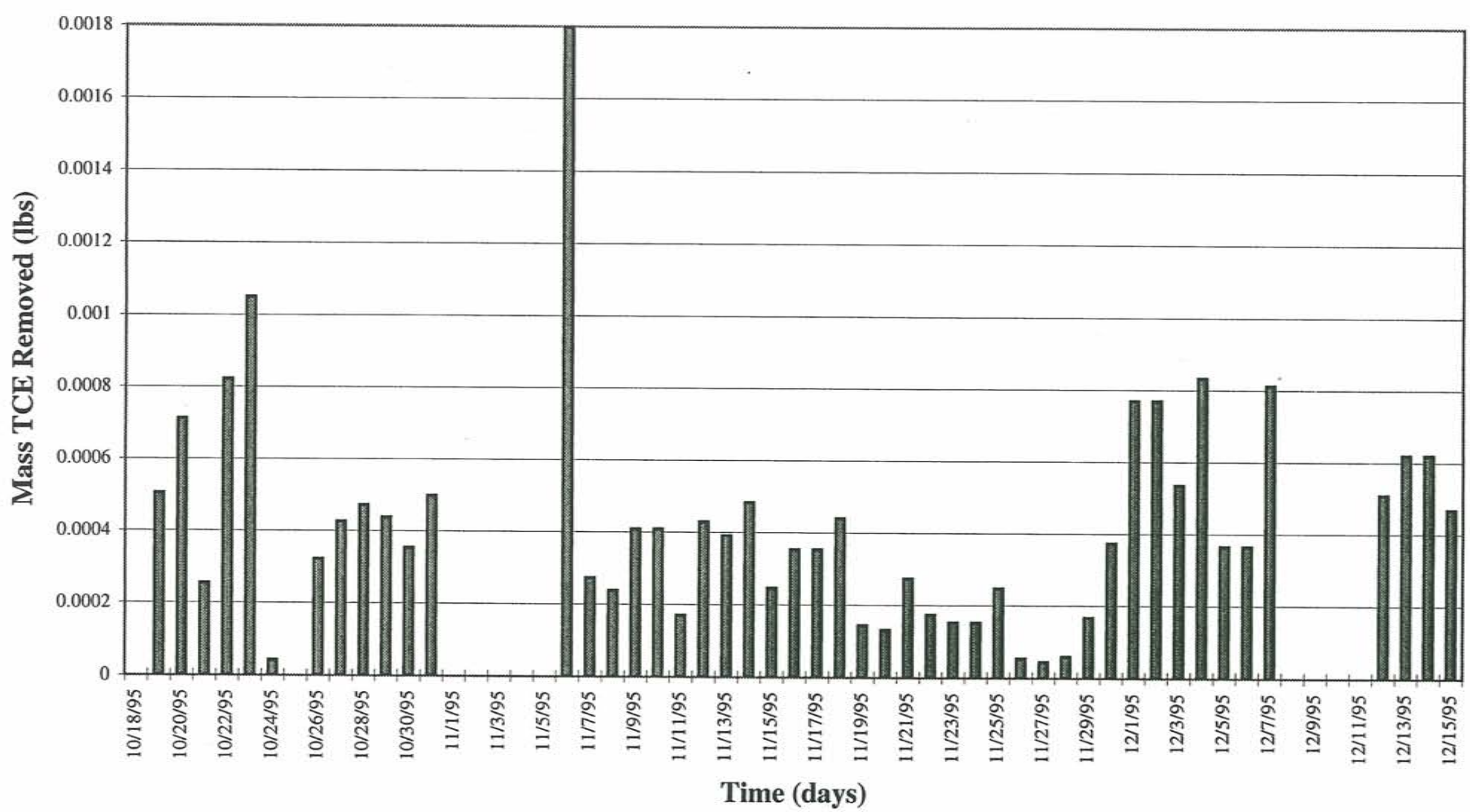
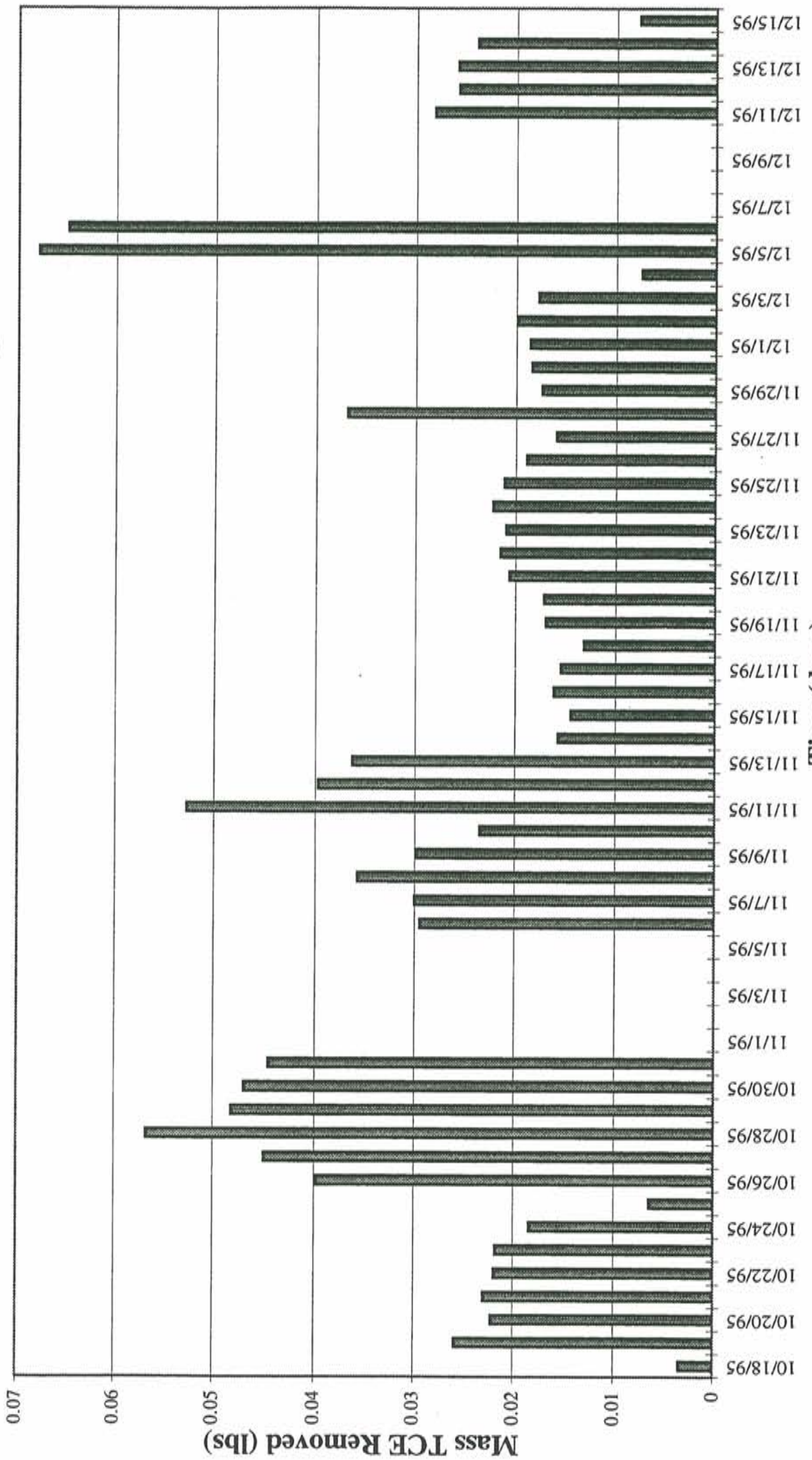


Figure 3-10. Two Phase TCE Mass Removal Per Day (Vapor)



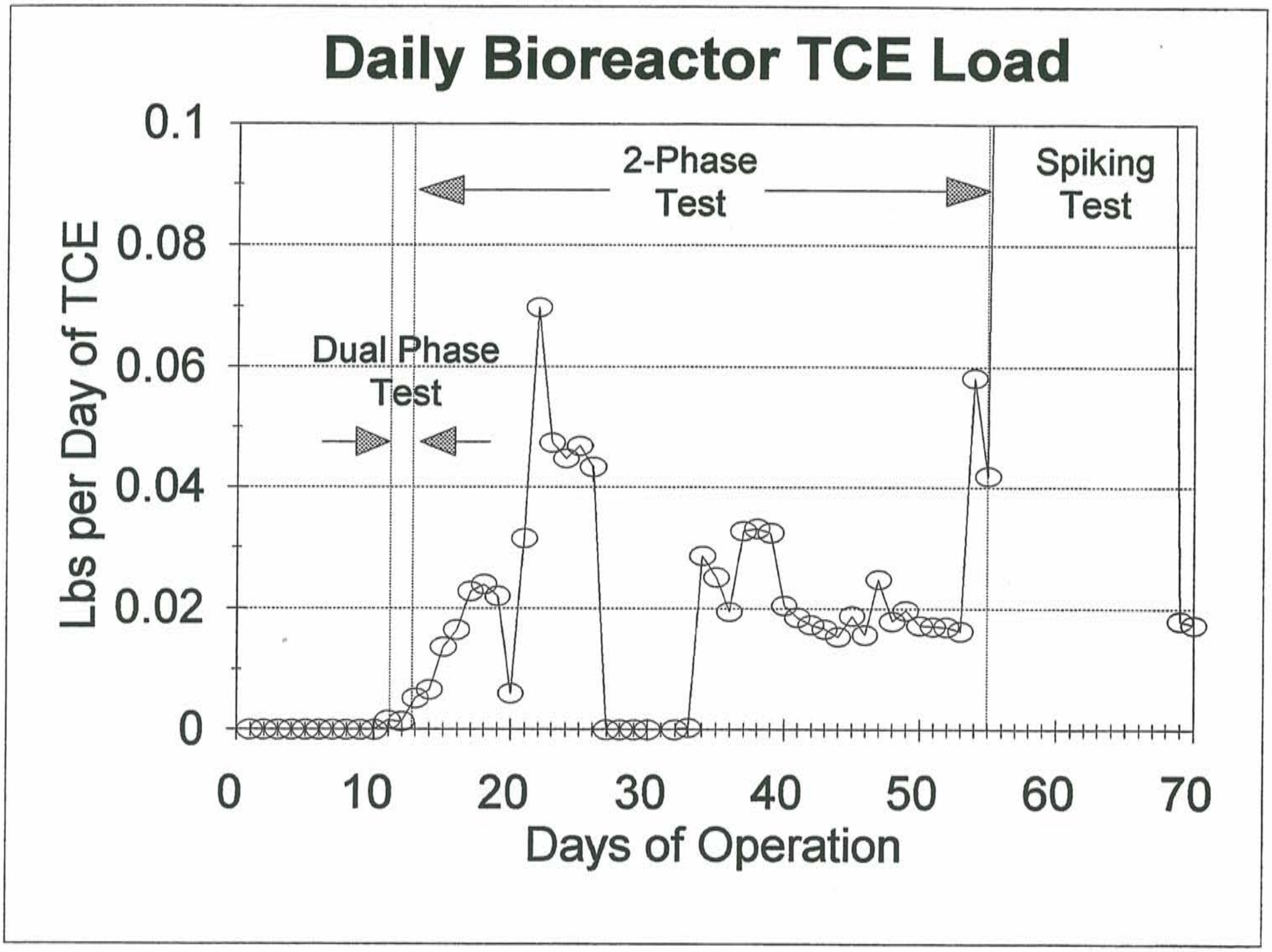


Figure 3-11a. Daily Bioreactor TCE Load (0.02 to 0.1 lbs per day scale)

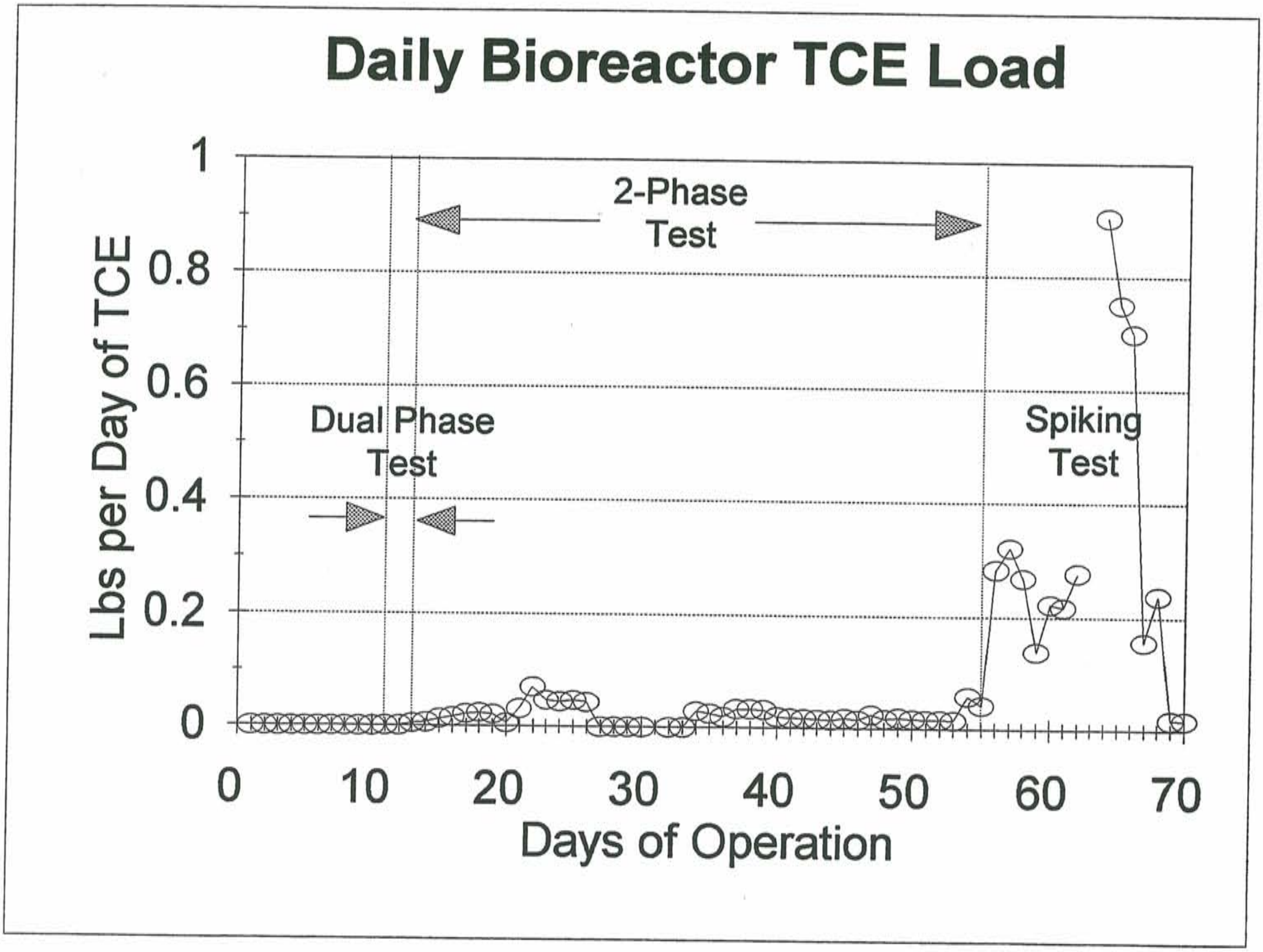


Figure 311b. Daily Bioreactor TCE Load (0.2 to 1.0 lbs per day scale)

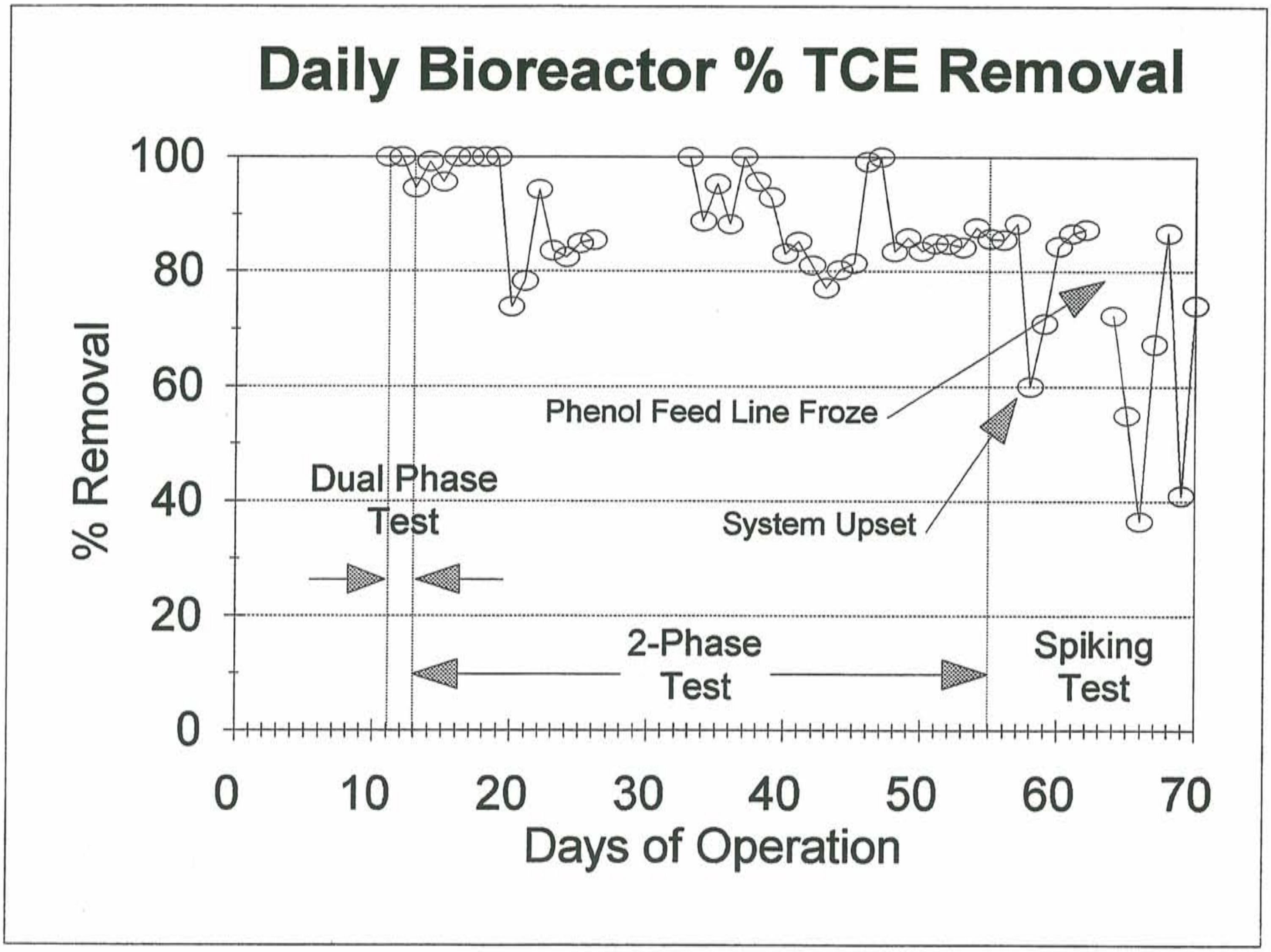


Figure 3-12. Daily Bioreactor TCE Removal Efficiency

(1) Total TCE Vapor Input = 0.93 lb;
(2) Total TCE Vapor Output = 0.10 lb;
(3) Total TCE Liquid Output = 0.00 lb; and
(4) Total TCE Removed = 0.83 lb [(1)-(2)-(3)].

Under normal operation, the phenol concentration in the bioreactor was less than the field assay detection limit of 0.1 ppm. However, on Days 31 (11/5/95), 47 (11/21/95), and 49 (11/23/95), minor mechanical system upsets caused the phenol concentration in the reactor to increase. At these times, the phenol feed pump was turned off until the phenol was consumed. In all three cases, the phenol was consumed within a 12- to 36-hour period. After the phenol concentration in the reactor dropped below 0.1 ppm, the phenol feed pump was restarted.

Table 3-3 below shows the operating parameters of the GPR system during the 2-Phase test.

Table 3-3
GPR Operating Parameters During the 2-Phase Test (10/18/95-11/29/95)

Operating Parameter	Range During 2-Phase Test	Avg. During 2-Phase Test
pH	6.8 to 7.7	7.3
Reactor Temperature (°F)	70 to 93	81
Biomass Density ($O.D._{550}$)	2.1 to 3.8	3.0
Make-up Water Rate (gpd$^+$)	10 to 115	69
Inlet Vapor Flowrate (scfm)*	4.2 to 7.7	54
Inlet TCE Conc. Range (μg/L)*^	12 to 115	55

$^+$assumed to be the same as the water discharge rate (excluding upset conditions)
*standard conditions = 14.7 psia and 77°F
^does not include concentrations during 2-Phase system downtime

3.4 Gas-Phase Reactor System Tests

3.4.1 Abiotic Loss Test

The results of the abiotic loss test are shown in Figure 3-13. On the basis of mass loading rates at steady state, the average abiotic loss of TCE from the system for any set of influent and effluent vapor samples was 7%.

Table 3-4 below shows the operating parameters of the GPR system during the abiotic loss test.

Table 3-4
GPR Operating Parameters During the Abiotic Loss Test (9/29/95-10/1/95)

Inlet Vapor Flowrate (scfm)	Avg. Inlet TCE Concentration (standard μg/L)	Outlet Vapor Flowrate (scfm)	Avg. Outlet TCE Concentration (standard μg/L)
11.1	370	13.1	285

Standard conditions = 14.7 psia and 77°F

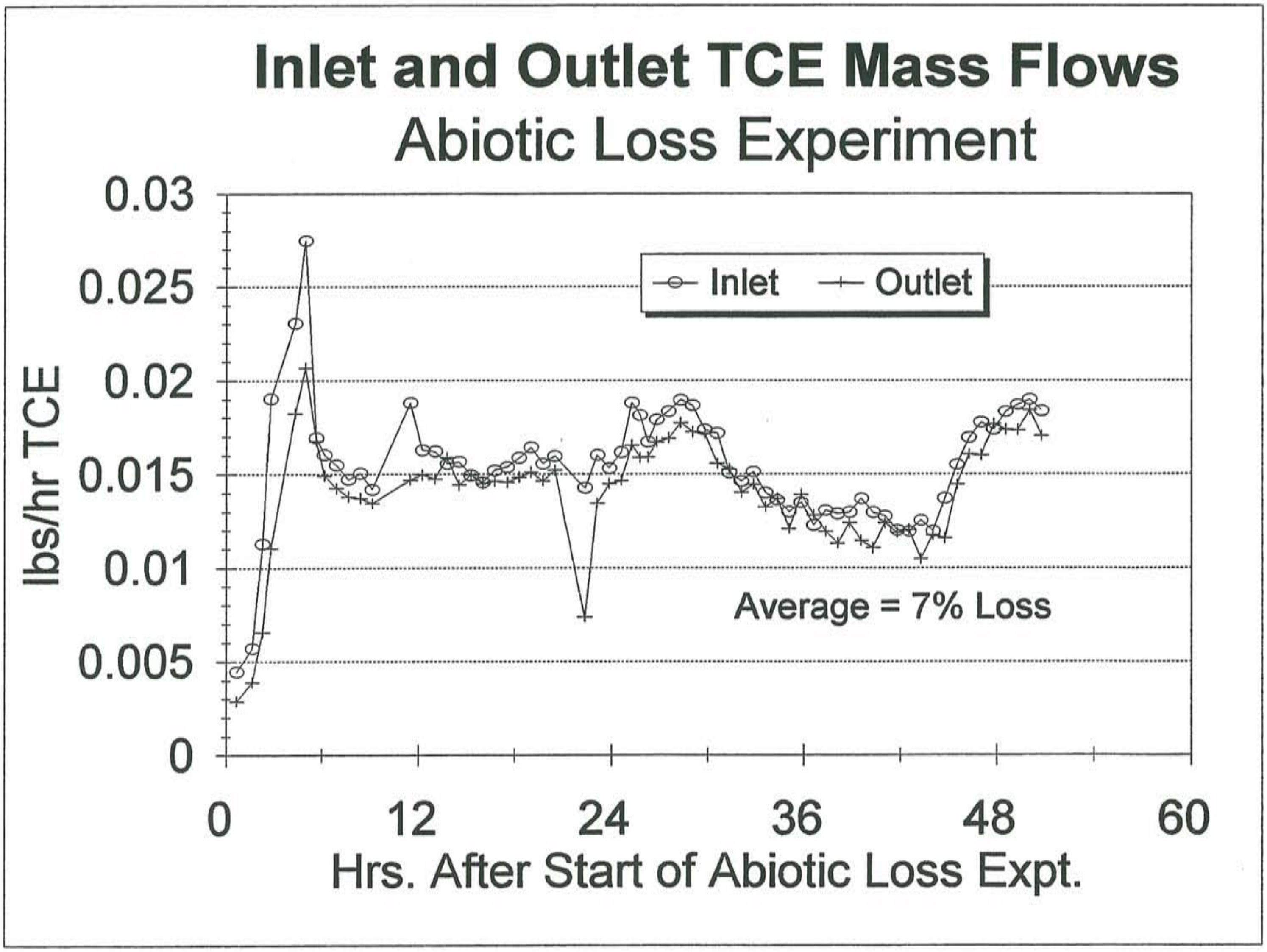


Figure 3-13. Results ofAbiotic Loss Test

3.4.2 TCE Spiking Test

Figures 3-11b and 3-12 show the daily bioreactor TCE load and removal efficiency, respectively, during the TCE spiking test. The inlet TCE load to the bioreactor during the TCE spiking test was approximately 10 times higher than during the 2-Phase test (0.2-0.9 lb per hour during the spiking test versus 0.02-0.07 lb per hour during the 2-Phase test). For the first seven days of the spiking test, the TCE removal efficiency was approximately 85%, except during a mechanical system upset on Day 58 (12/2/95), which caused the phenol concentration in the bioreactor to increase. However, within 48 hours, after the upset condition had been corrected, the removal efficiency returned to 85%.

On Day 63 (12/7/95), because of extremely low temperatures, the phenol feed line froze, eliminating a continuous supply of phenol to the reactor. The following day, the nutrient (N, P, and trace metals) feed lines also froze. Outside temperatures remained very low over the next four days, and phenol had to be manually added batchwise to maintain biological activity. Because of the batchwise addition, the phenol concentration in the bioreactor fluctuated during this period, which resulted in low TCE removal. The phenol and nutrient feed pumps were restarted on Day 67 (12/11/95), but the biomass could not quickly adjust to the continuous supply of phenol, and the phenol concentration had built up in the reactor after two days. The TCE removal efficiency after the phenol feed line froze until the end of the spiking test varied from 40% to 85%, and averaged approximately 60%.

The total amount of TCE processed through the bioreactor up to the time when the phenol feed line froze was 2.66 lb, and approximately 85% (2.23 lb) of the TCE was removed. U.S.G.S. analyzed the TCE concentration of the bioreactor discharge water two times during the TCE spiking test. On the first occasion, the TCE was below detection limit; on the second occasion, the TCE was detected at only 1.2 ppb. During the spiking test, approximately 700 gal. of water were discharged from the bioreactor.

On the basis of the results above, a total TCE mass balance around the bioreactor through Day 63 yielded the following results:

(1) Total TCE Vapor Input = 2.66 lb;
(2) Total TCE Vapor Output = 0.43 lb;
(3) Total TCE Liquid Output = 0.000007 lb; and
(4) Total TCE Removed = 2.23 lb [(1)-(2)-(3)].

Table 3-5 below shows the operating parameters of the GPR system during the TCE spiking test.

Table 3-5
GPR Operating Parameters During the TCE Spiking Test (11/29/95-12/12/95)

Operating Parameter	Range During TCE Spiking Test	Average During TCE Spiking Test
pH	6.9 to 8.2	7.3
Reactor Temperature (°F)	78 to 94	88
Biomass Density (O.D.$_{550}$)	1.8 to 4.0	3.0
Make-up Water Rate (gpd^{+})	40 to 72	56
Inlet Vapor Flowrate (scfm)*	4.2 to 7.4	5.3
Inlet TCE Conc. Range (μg/L)*^	255 to 1,357	739

$^{+}$assumed to be the same as the water discharge rate (excluding upset conditions)
*standard conditions = 14.7 psia and 77°F
^does not include concentrations during system downtime

3.4.3 Killed Control Test

The average loss of TCE from the system during the killed control test was 18%. Although this number is greater than the 7% loss observed during the abiotic loss test, it is likely that the biomass was not completely "killed" by raising the pH to 10, and that some low level of activity persisted. However, the results confirm that the major cause of TCE removal within the bioreactor was due to biological activity, and not abiotic mechanisms.

Table 3-6 below shows the operating parameters of the GPR system during the killed control test.

Table 3-6
GPR Operating Parameters During the Killed Control Test (12/14/95-12/15/95)

Inlet Vapor Flowrate (scfm)	Avg. Inlet TCE Concentration (standard μg/L)	Outlet Vapor Flowrate (scfm)	Avg. Outlet TCE Concentration (standard μg/L)
4.8	46	4.9	36

Standard conditions = 14.7 psia and 77°F

3.5 Total Atmospheric Discharge

Total discharge of TCE to the atmosphere from all sources during the treatability study was 1.7 lb (see Appendix E). This was far below the limit of 100 lb set by the Wyoming Department of Environmental Quality for the study.

3.6 Aquifer Testing

The shallow aquifer beneath the OU 2 Plume C site consists of a heterogeneous, unconsolidated formation consisting primarily of interbedded silty sands, gravelly clayey sands, and clays. Water levels in the piezometers on site range from about 7 to 13 ft bgs and groundwater flows to the northeast at a gradient of about 41 ft/mile. Groundwater data collected before and after the pilot testing at OU 2, Plume C show a background water table drop of approximately 2.25 ft from 1 October to 22 January 1996, as shown in Figure 3-3. Water table measurements for monitoring wells at other sites on Base show a similar drop over time. This background water table drop should be taken into consideration when analyzing the drawdown observed in the piezometers throughout the duration of the three pilot tests.

Aquifer test calculations are presented in Appendix F.

3.6.1 Aquifer Tests at Site

Three different tests were conducted on the extraction well and piezometers at the site to determine the hydraulic conductivity of the aquifer. The U.S.G.S. conducted slug tests, and Radian performed pumping and recovery tests. The results of the three tests are described below, and the hydraulic conductivities calculated by each method are summarized in Table 3-7.

Table 3-7
Aquifer Test Results, OU 2 Plume C

Well	Slug Test K (cm/sec)	Slug Test K (ft/day)	Recovery Test K (cm/sec)	Recovery Test K (ft/day)	Pumping Test K (cm/sec)	Pumping Test K (ft/day)	Pumping Test S (unitless)
P-1	--	--	0.0016	4.44	0.0032	9.12	0.0020
P-2	--	--	0.0090	25.50	0.0084	23.93	0.0030
P-3	--	--	--	--	0.0103	29.12	0.0040
P-4	--	--	--	--	0.0137	38.89	0.0009
P-5	--	--	--	--	0.0124	35.05	0.0060
MW-111	0.0153	43.34	0.0103	29.28	0.0082	23.21	0.0060
EW-1	0.0040	11.24	--	--	--	--	--

Notes:
-- = No data available for this well.
cm/sec = centimeters per second.
ft/day = feet per day.
K = Hydraulic conductivity.
S = Storage coefficient or storativity.

Slug Test

The U.S.G.S. performed slug tests on both the extraction well (EW-1) and an adjacent monitoring well/piezometer (MW-111) on site. The calculated hydraulic conductivity in EW-1 was 4.0×10^{-3} cm/sec (11.24 ft/day), and in MW-111 it was 1.5×10^{-2} cm/sec (43.34 ft/day). The hydraulic conductivity measured in the well is believed to be primarily representative of the clayey sand unit at the base of the screened interval (see Figure 1-3).

Pumping Test

Radian conducted a pumping test at the site from 1 to 5 October 1995 as part of the data collected for the pump and treat test. The pumping test data were analyzed using the Boulton method (described in Lohman, 1979), from which the hydraulic conductivity and storage coefficient were determined for the aquifer at each piezometer.

Hydraulic conductivities in the piezometers ranged from 3.2×10^{-3} cm/sec (9.12 ft/day) in P-1 to 1.4×10^{-2} cm/sec (38.89 ft/day) in P-4. The geometric mean of the pumping test-derived hydraulic conductivity values for the site is 8.5×10^{-3} cm/sec (24.2 ft/day).

The pumping test data were also used to calculate the aquifer storage coefficient, or storativity. The storage coefficient (S) is a unitless value that describes the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. The storativity ranged from 2×10^{-3} in P-1 and P-2 to 9×10^{-4} in P-4.

The S values calculated from the pumping test data are typical of confined aquifer values. This indicates that most of the water released from the aquifer came from aquifer compressibility, and not from gravity drainage, as is the case for a typical unconfined aquifer. The S values support the conclusion that the majority of the water recovered during the tests was probably from the clayey sand, which is below the clay layer and is probably under localized semiconfined conditions at the site.

Recovery Test

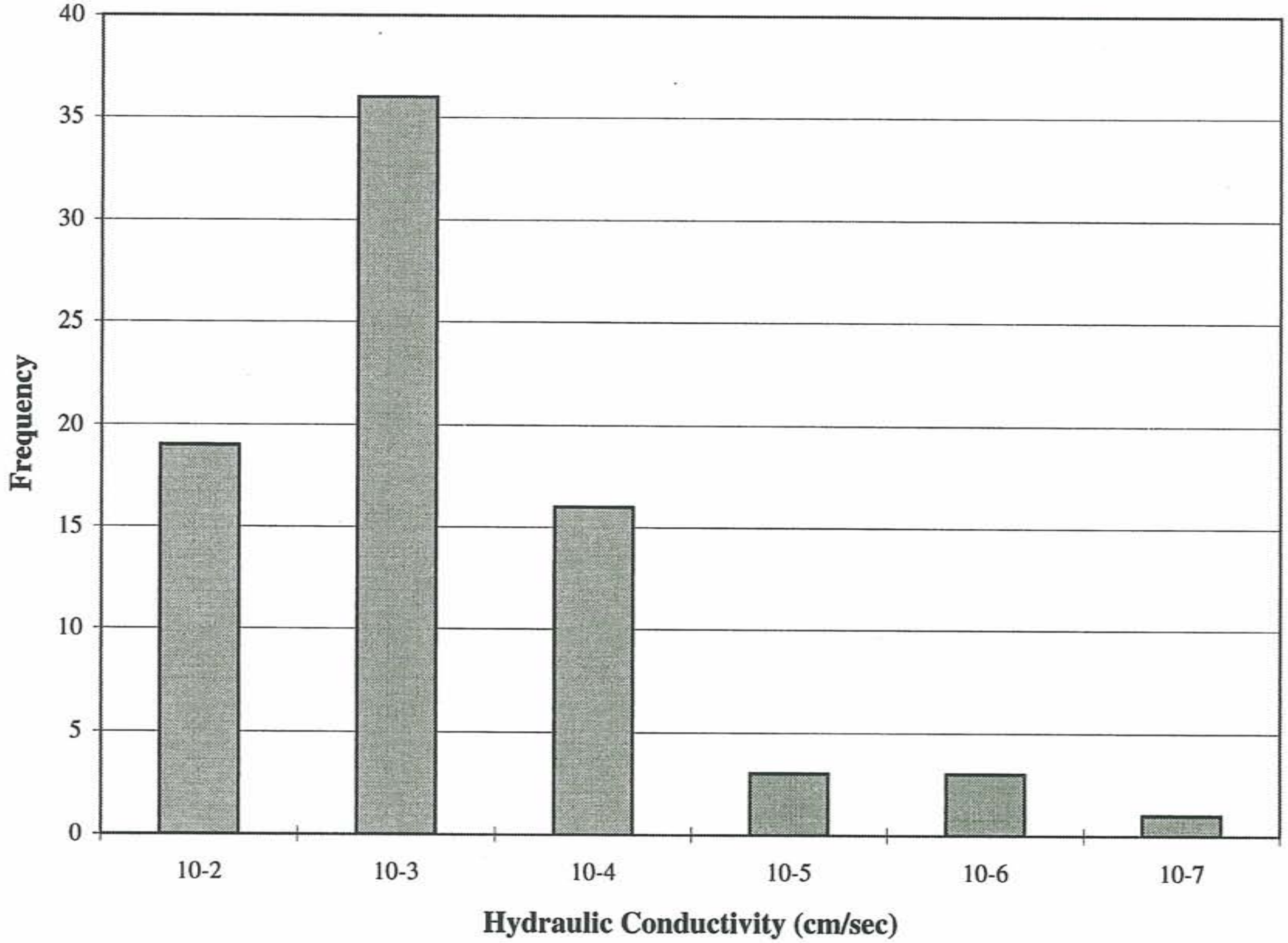
Radian conducted a recovery test in the piezometers P-1, P-2, and MW-111 on 15 December 1995, following completion of the 2-Phase pilot test. The recovery test data were analyzed by the Cooper-Jacob method (described in Lohman, 1979). The aquifer hydraulic conductivity was then calculated for each piezometer tested.

Hydraulic conductivities in the wells ranged from 1.6×10^{-3} cm/sec (4.44 ft/day) in P-1 to 1.0×10^{-2} cm/sec (29.28 ft/day) in MW-111. The geometric mean of the recovery test-derived hydraulic conductivity values for the site is 5.3×10^{-3} cm/sec (14.9 ft/day).

3.6.2 Base-Wide Slug Test Data

Information from slug tests performed by the U.S.G.S. at F.E. Warren AFB was compiled and analyzed to obtain an understanding of the hydraulic conductivity variation across the Base. The hydraulic conductivity values are primarily from wells located at sites LF3 and LF6. Figure 3-14 summarizes the distribution of hydraulic conductivity at F.E. Warren AFB, based on these data. The majority of the calculated hydraulic conductivity values on base are on the order of magnitude of 10^{-3} cm/sec. The geometric mean of the hydraulic conductivity values is 1.71×10^{-3} cm/sec (4.84 ft/day). This is slightly tighter than the values calculated for the test site.

Figure 3-14
Hydraulic Conductivity Distribution
F.E. Warren AFB, Wyoming



Section 4
CONCLUSIONS

The pilot-scale test at F.E. Warren AFB demonstrated that the 2-Phase extraction process and the Envirogen gas-phase reactor can be sucessfully integrated to remove and biotreat TCE in groundwater and soil. The integrated technologies should have widespread applicability as an effective soil and groundwater TCE recovery and treatment method.

The test also showed that at this site, flow from the moderate-permeability formation was only slightly different between pump and treat, dual phase, and 2-Phase extraction methods, but that flow increased with the application of vacuum to the well bore. Greater drawdown and higher mass removal rate were obtained with the 2-Phase process over the other extraction methods.

Because of the evolution of the scope of the project, it was not possible to do a definitive comparison of the three extraction methods. The objective of comparing these technologies was added to the scope after the Treatability Study Test Design was completed and all wells and equipment were in place. The wells and equipment were designed for the test of the integrated 2-Phase extraction and bioreactor treatment of TCE. The design and installation of the equipment for the pump and treat and dual phase methods was performed in the field at the start-up of the project. Consequently, there are limitations inherent in the data which must be considered. For example, in order to more directly compare the effectiveness of the methods, it would be desirable to achieve the same drawdown in the well. Because of the limitations of pumps, which must be submerged, less drawdown in the pump and treat and dual phase tests was achieved in the test well. This limitation could have been corrected by drilling the well deeper and inserting a blank well screen (sump) at the bottom of the well if the objective of a technology comparison had been identified prior to well installation. Another limitation in comparing the general applicability of these technologies is that dual phase systems more commonly use a lower vacuum blower, such as a regenerative or rotary lobe blower, rather than a more expensive high vacuum liquid ring pump. The liquid ring pump on the 2-Phase skid was throttled back to the limit of the equipment and still produced a higher vacuum for the first part of the dual phase test than was desired. Therefore, a comparison of system performance under similar vacuums between dual phase and 2-Phase was not possible. The 2-Phase system was operated to maximize the vapor concentrations to the bioreactor, rather than to maximize water production or vacuum on the formation. The straw size was reduced during the test for this purpose; typically the largest straw size possible is used. Finally, many conditions affect the proper choice of extraction equipment at a site. Hydraulic conductivity, water production rate, permeability to gas flow, depth to groundwater, and other factors are variables to be considered. This test was conducted on one extraction well at one site. Extrapolating results to other site conditions is somewhat speculative. However, the results of this test will be added to the data base of knowledge for other tests to help determine where the technology is most applicable.

The following conclusions were reached as a result of the demonstration at F.E. Warren AFB:

1) The 2-Phase process can be successfully integrated with Envirogen's gas-phase reactor to extract and treat TCE from soil and groundwater. Biotreatment would be most cost effective at sites yielding moder-

ate to high concentrations of TCE in the vapors.

2) Overall TCE mass removal rate with the 2-Phase process was 2-3 times greater than with pump and treat and dual phase extraction. This was likely attributable to greater drawdown and a larger desaturated zone and exposed well screen during the 2-Phase portion of the test. This allowed TCE sorbed onto the sediments to be stripped into the vapor phase. Pre-test TCE concentrations increased with depth, and these higher concentration zones were desaturated during the 2-Phase test. The greater drawdown was primarily attributable to the well configuration that required several feet of water for the pumps to operate during pump and treat and dual phase.

3) Greater than 95% of the dissolved TCE in the groundwater was stripped into the vapor phase by the 2-Phase process. Polishing with activated carbon removed the small residual. Groundwater concentrations of TCE ranged from about 200 to 1000μg/L during the test.

4) Greater than 98% of all TCE removed during 2-Phase (vapor plus water) was in the vapor phase. This is primarily attributable to the stripping of the groundwater inherent in the process. About 12% of TCE removed during dual phase was in the vapor phase.

5) The gas-phase reactor demonstrated 85% to 90% TCE removal efficiencies at inlet TCE concentrations ranging from 10 to 700 μ/L (@ 17.7 psia and 150°F). On the basis of these results, the gas-phase reactor is a viable option for treating TCE-contaminated vapor streams.

6) Groundwater flow from the formation was increased with the application of vacuum to the well bore. The highest flow was achieved during dual phase treatment with the maximum available vacuum (23 in. Hg) applied. This is a higher vacuum than is most commonly used in a dual phase application.

7) The difference in groundwater extraction between pump and treat, dual phase, and 2-Phase was not large at this site (total flow range of 2-4 gpm). The moderately productive formation ($K = 10^{-2}$-10^{-3} cm/sec) yielded significant flow even under standard pump and treat conditions. A tighter formation ($K<10^{-3}$ cm/sec) would likely show a more dramatic difference in flow between the extraction methods.

The following general conclusions are not based strictly on the results of this test, but are based on process knowledge and experiences at other sites:

1) 2-Phase is likely to be more cost effective in tighter formations, and pump and treat or traditional (low vacuum) dual phase is likely to be more cost effective in more productive formations. This is primarily because the increase in flow obtained with 2-Phase as compared with the other technologies is likely more dramatic in tighter formations. High vacuum dual phase may be more cost effective in tighter formations with low TCE concentrations where water treatment expense at the surface would be lower. The data generated from this test were insufficient to evaluate this fully.

2) Advantages of 2-Phase typically include treatment (stripping) of the groundwater

during the extraction process; larger dewatered area in a given well, which allows greater treatment zone and contaminant mass removal; very simple downhole equipment (pipe only); and no external compressor required to operate the pump.

3) Advantages of dual phase typically include increased contaminant mass removal compared with pump and treat (although this was not supported by this test), less complex above-ground equipment compared with 2-Phase, and flow enhancement in more productive formations with more modest vacuum equipment.

Section 5
TECHNOLOGY APPLICATION

5.1 Groundwater Pump and Treat

Groundwater pump and treat technology has proved to be appropriate for many hydrogeological conditions, waste types, and chemical properties, but is typically used in high permeability formations. It is the technology selected at more than 90% of sites with final Records Of Decision. For problems involving significant groundwater contamination, some form of pump and treat technology (whether it be for remediation or containment) has consistently been used and will continue to be used.

Choosing pump and treat technology to contain groundwater contamination at a site has been a frequent choice because of the following:

- Pump and treat is a widely proven technology;
- There have been no other "widely" demonstrated technologies that will accomplish the same objectives;
- Pump and treat can be easily used in conjunction with vadose zone remediation technology (i.e., soil vapor extraction or bioventing) and/or other containment technologies (i.e., capping) to minimize the potential threats to human health or the environment;
- Pump and treat is versatile and can be used for either contaminant plume "hot spot" or leading-edge containment or both; and
- Pump and treat system components are readily available.

Pump and treat is most commonly recommended for plume containment. It is most applicable in higher permeability formations where a significant flow and radius of influence can be achieved. It is a relatively simple and easy to implement technology. However, mass removal rates are typically low, and over the long term, it frequently cannot obtain remediation goals because it does not remove contaminants adsorbed onto the soils.

5.2 Dual Phase Extraction

The application of groundwater pumping and soil vapor extraction in the same well is an integrated remedial strategy for hydrocarbon- and VOC-impacted soils and groundwater. It is generally most applicable in moderate to highly permeable formations. With dual phase, dissolved VOCs contained in the groundwater must be treated at the surface.

This technique has most commonly been implemented with low vacuum, but can be done with high vacuum (Sittler, et al, 1994). The effectiveness of low-vacuum dual phase extraction can be severely restricted as formation permeability decreases.

The application of high vacuums has been successful at remediating soils and groundwater at sites that are not amenable to conventional pump and treat/vapor extraction techniques. High vacuum (up to 25 in. Hg) is applied to an extraction well or a network of extraction wells to increase groundwater recovery rates and maximize subsurface air flow in low permeability formations. This creates a large capture zone for a single well or increased capture zones of well systems, and substantially increases site dewatering. Through dewatering of the site, vapor extraction of the

previously saturated sediments occurs, which results in increased volatilization of organic compounds and increased mass removal rates.

5.3 2-Phase Extraction

The 2-Phase extraction process was developed for the remediation of VOCs and other contaminants in soil and groundwater. It is generally most applicable in low- to moderate-permeablilty subsurface formations. 2-Phase extraction removes liquid, vapor, and absorbed contaminants from soil at a high rate, and subjects a large soil volume to treatment. VOCs are stripped from the groundwater in this process, transferring most of the contaminants to the vapor phase and requiring only polishing of the water phase.

The 2-Phase technology will outperform pump and treat methods for groundwater extraction in formations with low yields because 2-Phase systems augment gravitational flow to the extraction wells with a continuously applied high vacuum. The ability of 2-Phase technology to simultaneously pull air through the dewatered zone results in the removal of contaminants adsorbed to soil particles and/or held by capillary forces in interstitial zones. Pump and treat systems do not effectively remove contaminants in these areas, nor would low vacuum dual phase be very effective because of the low permeabilities.

The 2-Phase process also provides significant groundwater treatment as part of the process, reducing treatment cost. Vapor and entrained liquid from the extraction well are conveyed under vacuum up the straw to the surface equipment. The reduced pressure and extreme turbulence in the formation, straw, and hose transfers (strips) VOCs from the liquid phase to the vapor phase. In this demonstration, over 95% of the TCE in the groundwater was stripped in the 2-Phase process. The resultant liquid phase generally only requires polishing prior to discharge, and the vapor phase can be treated (as in this demonstration) or vented according to regulations.

2-Phase extraction could be effectively implemented for contaminant removal, plume containment, or plume regression to "pull" the contaminated groundwater that has migrated across property boundaries.

5.4 Extraction Technologies Capital and Operating Cost Comparison

A life cycle cost comparison of typical 2-Phase and dual phase extraction systems was performed using different groundwater TCE concentrations. Assumptions were:

- Five extraction wells at 25 ft deep (cost of well installation not included).
- 75 scfm total vapor flow (15 scfm per well at 14 in. Hg).
- 15 gpm total water flow (3 gpm per well).
- Dual phase capital cost $26,000 based on skid-mounted 7.5 hp vacuum module, water pumps, 15 hp compressor and accessories.
- 2-Phase capital cost $14,000 based on 25 hp skid-mounted vacuum module.
- Additional capital cost for installation of each system $150,000.
- Annual costs based $0.07/KWH, $2/lb carbon replacement cost.
- Water phase is treated with granular activated carbon (GAC). Carbon usage for liquid-phase GAC is based on TCE isotherm data from Carbtrol; no safety factor applied. Vapor phase treatment not included.

- 90% stripping efficiency obtained in 2-Phase process.

- Labor to operate and maintain and cost of replacement parts are equal between the two systems and are not included.

- Typical duration of remediation by 2-Phase is 2-5 years. 5-year life cycle is costed.

- Three TCE concentrations in groundwater are used: 500, 5000, and 50000 g/L.

The results of the cost analysis are shown in Figure 5-1. The analysis shows that at lower concentrations, the two systems are roughly equivalent in cost. At higher concentrations, 2-Phase is more cost effective.

5.5 Gas-Phase Reactor

5.5.1 Gas-Phase Reactor Description

Envirogen's mid-size gas-phase reactor (GPR) system is capable of treating 100 to 150 cfm of TCE-contaminated air with a typical removal efficiency of 90% TCE. The 100 to 150 cfm vapor treatment capacity is within the range of most full-scale 2-Phase, soil vapor extraction (SVE), and many small-scale air stripping operations. The bioreactor vessel is an 11 ft diameter tank with a liquid capacity of 7500 gal., 10 times more liquid capacity than the field-pilot unit. The system is equipped with automatic pH control and antifoam addition, as well as nutrient and phenol feed tanks. The system is also heat-traced and insulated for cold weather operation. A 15 hp impeller is used to provide mixing and gas/liquid turbulence. Figure 5-2 is a diagram of the full-scale system.

5.5.2 Gas-Phase Reactor Treatment System Capital and Operating Cost Comparison

An economic evaluation was performed for the GPR system using different inlet TCE concentrations at a vapor flowrate of 120 cfm. Economic evaluations were performed for either an equipment-purchase option or an equipment-lease option. The full-scale GPR system capital cost was estimated at $125,000 installed on a customer-supplied foundation. For the equipment-lease option, the monthly lease rate for the system was estimated at $2,100. Bulk nutrient (100 lb bags) and caustic (55 gal. drums) costs were obtained from a bulk chemical supplier. The bulk phenol cost (tankcar lots— freight equalized) was obtained from the January 15, 1996, issue of Chemical Marketing Reporter. The operating labor requirement was assumed to be 0.25 man-years at $40,000 per man-year, and power costs were estimated using a value of $0.07/KWH for electricity. Maintenance materials (replacement parts, etc.) were estimated at 2% of the capital equipment cost.

Comparable capital and operating costs were developed for carbon adsorption using the same vapor flowrate and inlet TCE concentrations. Carbon consumption was based on TCE carbon isotherm data for Calgon BPL Activated Carbon fitted to a Freundlich equation, and changed significantly with concentration. At the suggestion of the manufacturer, for design purposes, the theoretical carbon usage rate determined from the isotherm data was multiplied by a factor of two to obtain the design carbon usage rate. The safety factor is an allowance for: (1) buildup of a "heel" of adsorbate on the carbon, not removed during carbon regeneration, which results in reduced

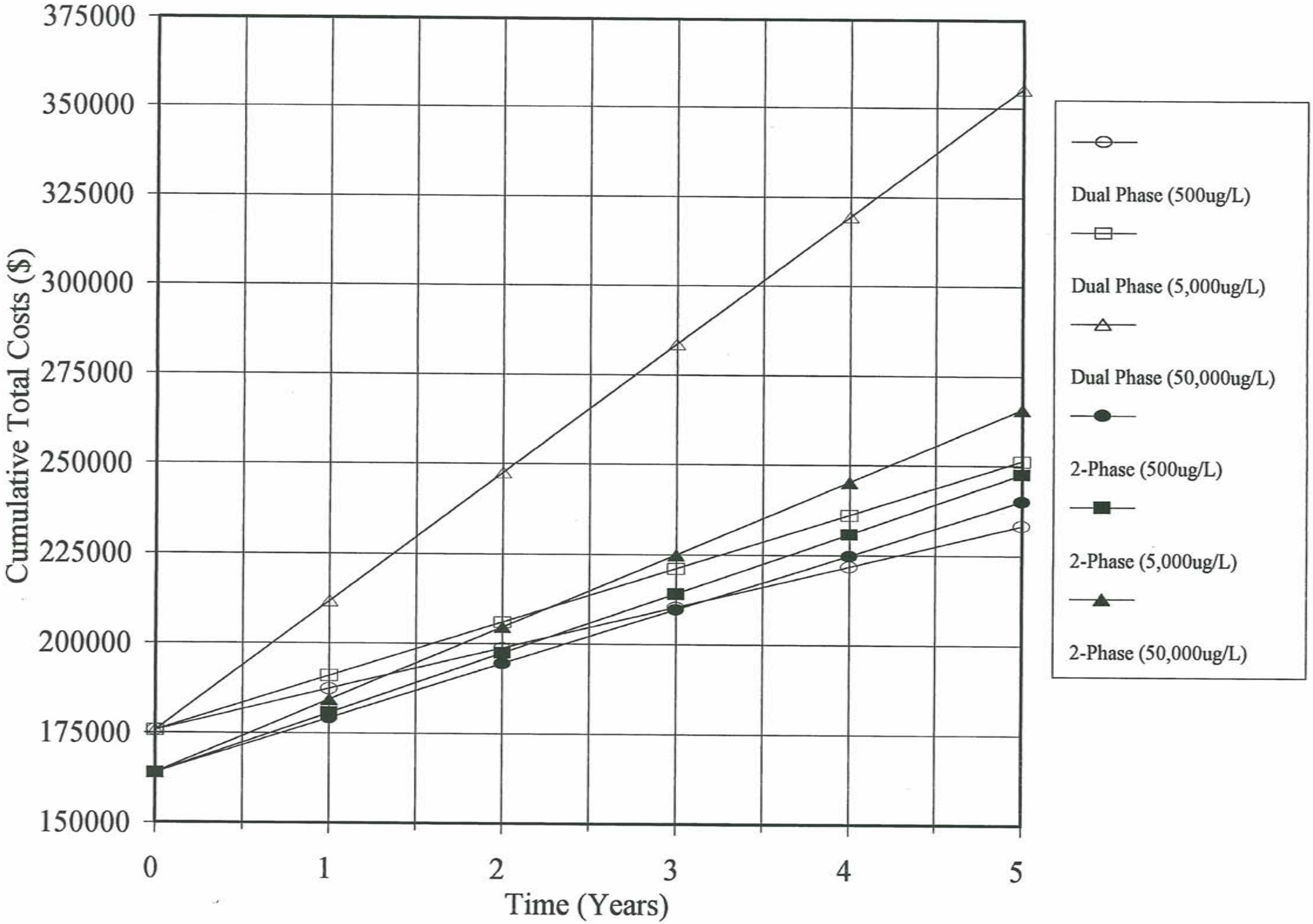


Figure 5-1. Life Cycle Cost of 2-Phase and Dual Phase Systems

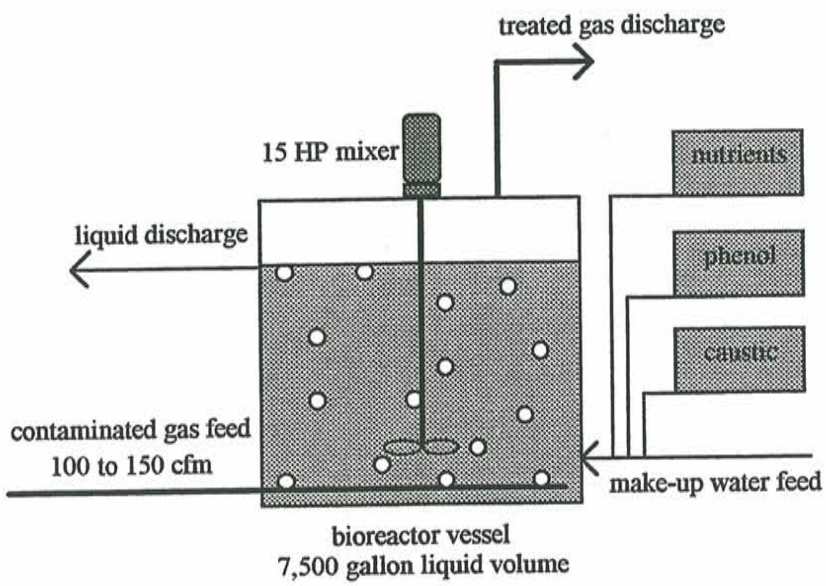


Figure 5-2. Full-scale GPR System Schematic

capacity, (2) fluctuations in stream composition, (3) humidity effects, and (4) effects of other contaminants in the air stream. At sites such as the F.E. Warren AFB site, where TCE is the only contaminant, this safety factor will likely result in an over-estimation of the carbon usage rate. This safety factor applies to the more general case, i.e., at a site with multiple hydrocarbon contamination along with TCE. Carbon replacement costs were set at $2.00 per pound, which included replacement carbon and extras such as vacuuming, shipping, removal, analysis, and disposal of spent carbon. Capital costs were estimated at $10,000 for a 1000 to 2000 lb carbon adsorption unit installed on a customer-supplied foundation. For the equipment-lease option, the monthly lease rate was estimated at $300. The operating labor requirement was assumed to be 0.1 man-years at $40,000 per man-year, and replacement parts were estimated at 2% of capital. The heating requirements to condition the inlet air are not included in the operating costs.

The costs for both the GPR and carbon adsorption systems described above do not include the installation and capital costs of an extraction system, including the associated system blower. In addition, the costs do not include the electrical operating costs to prevent the bioreactor system from freezing, nor the electrical heating costs to condition the influent air to the carbon adsorption system. Finally, the costs for the GPR system do not include the costs for carbon polishing, if required.

Two economic comparisons were conducted: (1) an equipment purchase option, and (2) an equipment lease option.

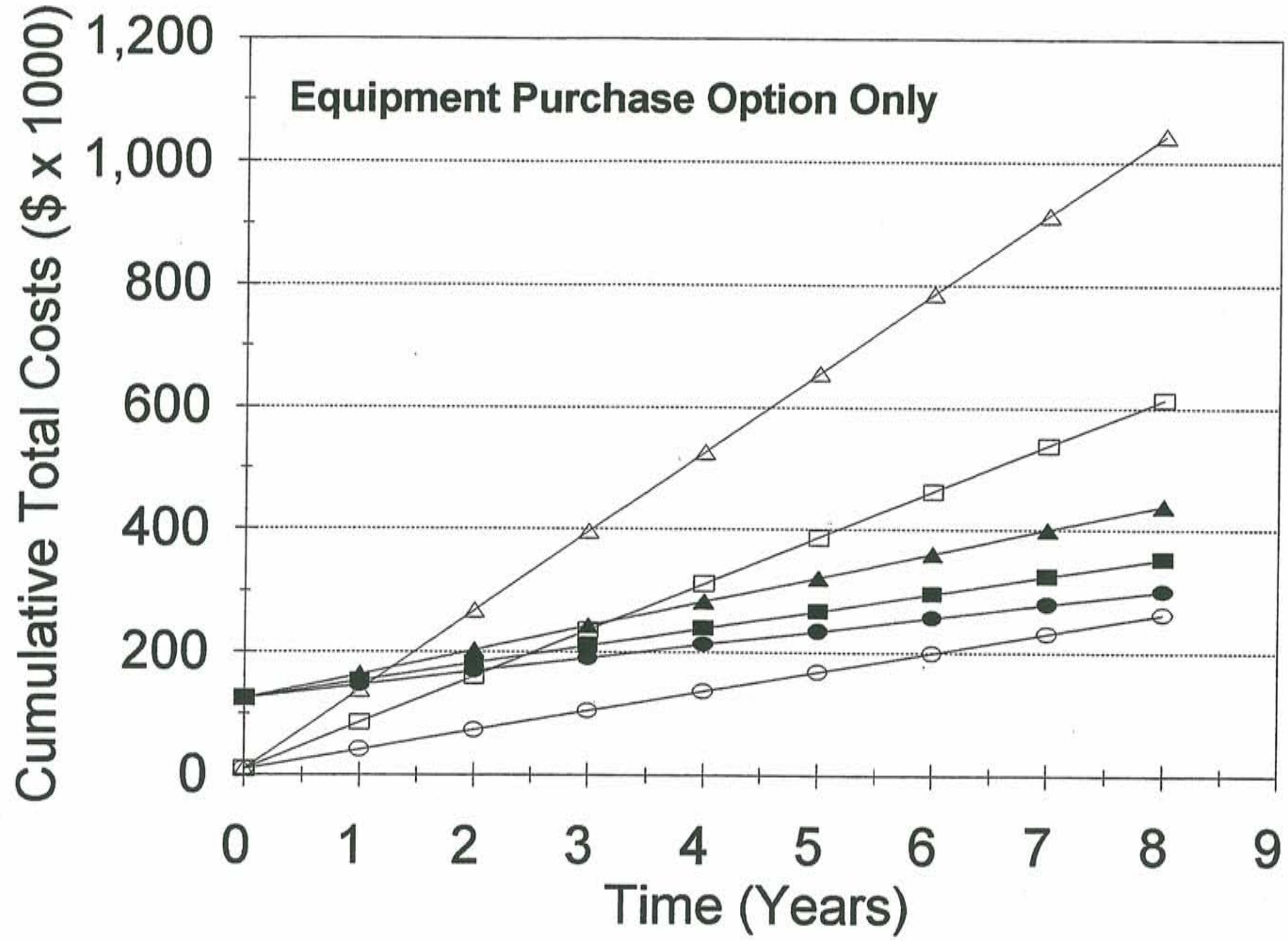
Equipment Purchase Option— Figure 5-3 shows the life cycle costs of the GPR and carbon adsorption systems as a function of TCE concentration for the equipment purchase option. Costs represent current dollars with no amortization period or interest rate factor. As shown in Figure 5-3, the economic competitiveness of the GPR system increases with increasing TCE concentration.

Equipment Lease Option—Figure 5-4 shows the yearly operating costs for the GPR and carbon adsorption systems for the equipment lease option. For a TCE concentration of 1000 μg/L (190 ppmv) over a three-year project life, the cost savings are estimated to be approximately $75,000 if a GPR system is leased as compared to lease of a carbon adsorption system.

5.5.3 Gas-Phase Reactor Treatment System Conclusions

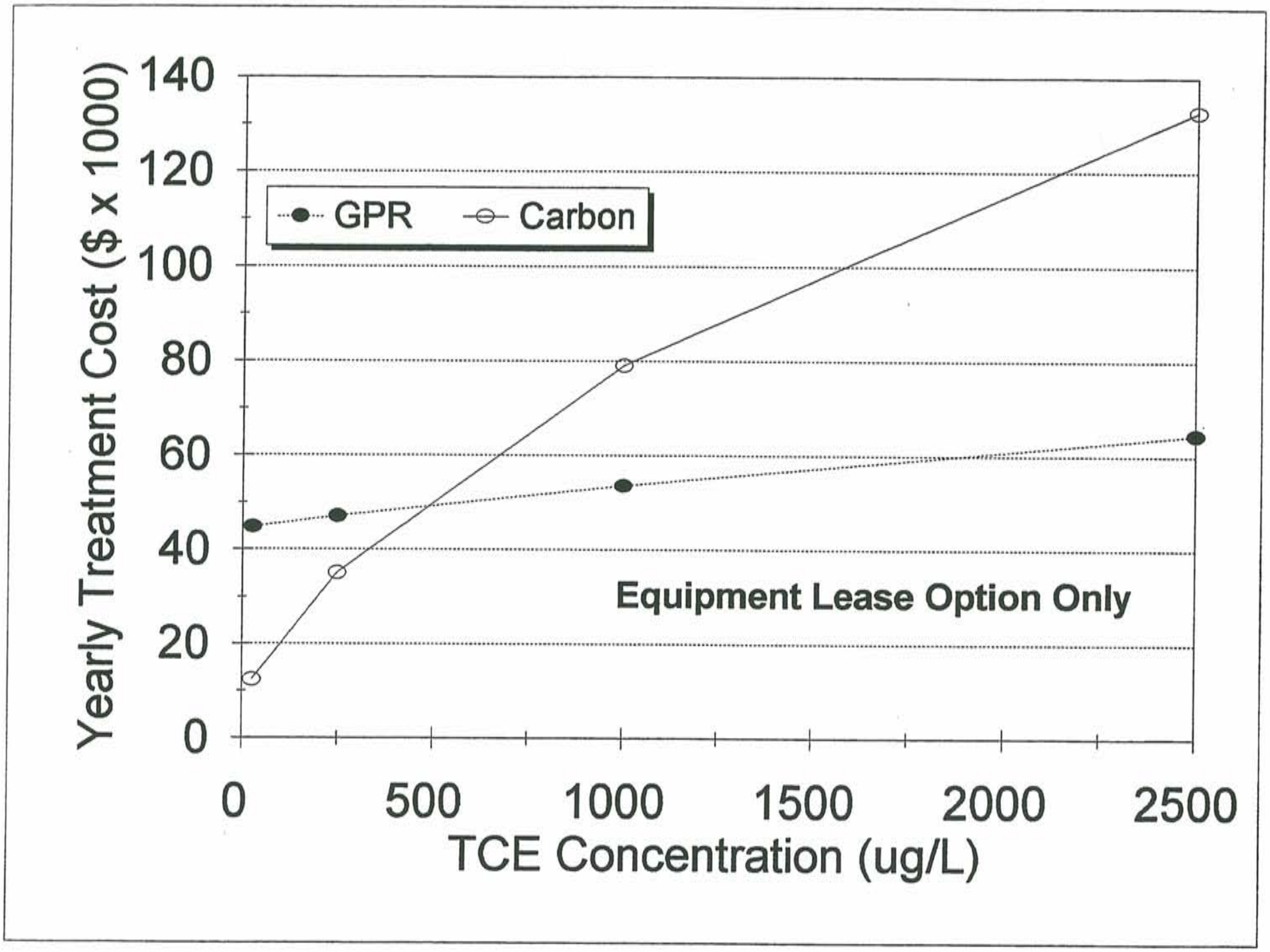
The GPR system is economically competitive for treatment of 100 to 150 cfm of air containing TCE concentrations in excess of 500 μg/L (90 ppmv). At higher TCE concentrations, the cost savings are greater.

In addition to economic advantages, the gas-phase reactor destroys TCE and does not merely transfer the TCE to another medium (such as carbon). The vapor discharge from the gas-phase reactor does not require further treatment, except in cases where extremely low TCE discharge levels are mandated. The bioreactor liquid effluent can be discharged to the local sanitary sewer; no further treatment or special processing is required.



Note: Costs represent current dollars with no amortization period or interest rate factor. The vapor flowrate treated is 120 cfm. The six curves are for the GPR at 250 µg/L [2.7 lbs/day] (●), 1,000 µg/L [10.8 lbs/day] (■), and 2,500 µg/L [27.0 lbs/day] (▲), and for the carbon adsorption system at 250 µg/L [2.7 lbs/day] (o), 1,000 µg/L [10.8 lbs/day] (□), and 2,500 µg/L [27.0 lbs/day] (Δ).

Figure 5-3. Life Cycle Costs of GPR and Carbon Adsorption System for the Equipment Purchase Option



Note: The vapor flowrate treated is 120 cfm. The concentration, in ppmv, is equal to the concentration, in μg/L, multiplied by 0.187.

Figure 5-4. Yearly GPR and Carbon Adsorption Treatment Costs for Equipment Lease Option

5.6 Integrated Technologies Application

Vacuum extraction integrated with gas-phase biotreatment would be applicable to address contaminated soil and groundwater at various sites across the Department of Defense. The vacuum extraction could be either the 2-Phase system or dual phase system, depending on permeabilities and groundwater flow from the subsurface formation. 2-Phase extraction would likely be applicable in low- to moderate-permeability with low groundwater yield formations, while dual-phase extraction would likely be applicable in formations that are medium- to high- permeability, with high groundwater yield.

Either extraction system could be integrated with the gas-phase biotreatment system. However, the 2-Phase extraction system produces significantly higher contaminant concentrations in the vapor that would make the bioreactor more cost effective. The dual phase extraction system would have to be implemented in a medium-to high-permeability formation with significant vados zone contamination to generate sufficient vapors for the bioreactor to be cost effective. Or, dual phase could be combined with surface treatment of groundwater via air stripping to increase the vapor concentrations to the bioreactor. Contaminant concentrations in excess of 90 ppmv would be desirable for the operation of the biotreatment system. Contaminant concentrations below these levels may reduce the cost effectiveness of the bioreactor system. If prolonged operation at low concentrations is expected, and cost is the only criterion for selection, alternative vapor-phase treatment should be considered.

With most treatment technologies, the disposition of effluent discharge and the treatment media creates waste that may be considered hazardous and would trigger hazardous waste disposal regulations. The bioreactor generates waste that is not considered hazardous and would meet most effluent discharge limits set by wastewater treatment facilities. The costs of disposal for treatment media and effluent wastes must always be considered when comparing vapor and water treatment technologies. The integration of high vacuum extraction and the vapor phase biotreatment makes waste handling less management intensive, hence would equate to lower overall operating costs for the system.

5.7 Future Test Design Considerations

The following should be considered for design of future tests:

- Aquifer characteristics from slug or pumping tests and recent soil and groundwater quality data should be obtained prior to deciding on a site. This could affect the selection of technologies. In a heterogeneous formation such as the Ogallala at this site, the actual extraction well should be tested prior to the demonstration because of potential dramatic differences over short distances.

- To perform a true comparison of extraction methods, a site should be selected and the test should be designed for this specific purpose. Different methods require different extraction well design and monitoring.

- An extraction test could be designed around one or more of the following three objectives:
  - -- Plume containment
  - -- Contaminant removal (hot spot)
  - -- Plume regression

  The relevant objective(s) should be incorporated into the site selection, well configurations, equipment specifications, and overall test design.
- Because of delays in the original schedule, this test extended into winter weather conditions which caused problems that

Section 6
F.E. WARREN AFB RECOMMENDATIONS

F.E. Warren AFB has been conducting a remedial investigation and is beginning a feasibility study for OU 2 and the other operable units on Base. OU 2 is comprised of several groundwater TCE plumes in various parts of the Base. Other OUs also include groundwater. At Landfill 3 (OU 3), a TCE plume has migrated off base. All of the plumes are old (typically 30 years or more).

The Base is interested in implementing early actions to address the further spread of contamination. For example, they have a pump and treat system involving air stripping of TCE at Spill Site 7 where contaminated groundwater is discharging to Diamond Creek. This system has operated intermittently. Bioventing studies to address hydrocarbon vadose zone contamination have also been performed at two sites.

There are three typical objectives in implementing groundwater actions:

- Plume containment;
- Hot spot removal; and
- Plume regression.

This study has demonstrated that 2-Phase extraction would be successful at aggressively extracting TCE (and other VOCs) from groundwater and the vadose zone at an accelerated rate. It would likely be effective for any of the above objectives, given the right site conditions. For example, hot spot removal at Plume C (the site of this study) and plume regression at Landfill 3, or possibly complete removal of the small plume at Landfill 3, are possible candidates. Depending on TCE concentrations and vapor discharge limitations by the State, integrated treatment with the gas-phase reactor may also be appropriate. Dual phase may be appropriate at more permeable sites. However, most sites on the Base have less permeable conditions than the test site (see Section 3.6.2). Slug testing should be performed at a site prior to selecting a technology.

Implementing a combination of the above three objectives could be accomplished as interim remedial actions (IRAs). This would move F.E. Warren AFB from the study phase into more of a proactive remediation agenda. A possible scenario is a series of short-term actions on the order of months using a mobile unit to accomplish hot-spot remediation. Additional interim actions could focus on containment and/or regression as needed. Such a program could address the major problems within a couple of years. This could be done prior to finalizing Proposed Plans and RODs.

Any action involving a TCE plume should include potentially deeper well installations and real-time field screening of cuttings for VOC content. Increasing concentrations of TCE were observed with depth during this study. This is probably because TCE is more dense than water. Greater mass removal would likely have been obtained with a deeper extraction well.

Further action at Plume C should focus on the area around and north of the extraction well (GW-1). Analysis of cuttings from piezometers to the north had significant concentrations of TCE, while piezometers to the east and southwest were non-detect. The Base is also planning a soil gas survey in this area. It would be desirable to complete this to get a better picture of the hot spot locations.